The Characterisation and Modelling of a Double-Layer Dunnage Bag

by

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Abstract

The Characterisation and Modelling of a Double-Layer Dunnage Bag

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Thesis: MEng (Mech)
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Dunnage bags are used to stabilize and secure cargo. Currently, the dunnage bags available are either single-layer dunnage bags which are expensive or inexpensive double-layer dunnage bags. However, due to the time-consuming production of a double-layer dunnage bag, an inexpensive single-layer dunnage bag material could be a viable alternative. The aim of the project is to develop a material criterion that can find candidate material properties that produce the same performance parameters as the current double-layer dunnage bags at the same cost. This material should provide the same properties and display the same behaviour at similar operating conditions as the original double-layer dunnage bag.

Accordingly, a material criterion, that consists of parametric mathematical models, are developed. These models are developed using load cases that the dunnage bags experiences, along with various theoretical equations that are linked and validated by experiments. Large-scale experimental case studies and smaller swatch tests are performed to determine the actual behaviour and material properties of the double-layer dunnage bags. The experimental data of the tensile tests are analysed by using constitutive modelling. Finally, to create a material criterion, a Monte Carlo Simulation is used to input material properties, based on a normal distribution. Then, the material properties are fed into a pass criterion that is used to filter various material properties while being compared to the output of the model parameters. This finally leads to correlated candidate material properties.

Uittreksel

Die Karakteriseering en Modelleering van n Dubbel-Laag Stusak

("The Characterisation and Modelling of a Double-Layer Dunnage Bag")

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April 2019

Stusakke word gebruik om vrag te stabiliseer en te beveilig. Tans is die stusakke beskikbaar in enkellaag sakke wat duur is of dubbellaagsakke wat goedkoper is. As gevolg van die tydrowende produksie van 'n dubbellaag stusak, word 'n goedkoper enkellaag stusakmateriaal ondersoek. Die doel van die projek is om 'n wesenlike kriterium te ontwikkel wat kandidaat materiaal eienskappe kan hê wat dieselfde prestasieparameters as die huidige dubbellaag stusakke teen dieselfde koste het. Hierdie materiaal moet dieselfde eienskappe verskaf en dieselfde gedrag vertoon by soortgelyke bedryfsvoorwaardes as die oorspronklike dubbellaagsak.

Gevolglik word 'n wesenlike kriterium wat uit parametriese wiskundige modelle bestaan, ontwikkel. Hierdie modelle word ontwikkel met behulp van lasgevalle wat die stusakke ervaar, tesame met verskeie teoretiese vergelykings wat deur eksperimente gekoppel en gevalideer word. Grootskaalse eksperimentele gevallestudies en kleiner steekproewe word uitgevoer om die werklike gedrag van die dubbellaagsakke te bepaal. Die eksperimentele data van die trektoetse word ontleed aan die hand van konstitutiewe modellering. Ten slotte, om 'n wesenlike kriterium te skep, word die Monte Carlo Simulasie gebruik om insette van materiële eienskappe te stuur, gebaseer op 'n normale verspreiding. Dan word die materiaal eienskappe gevoer in 'n slaag of druip kriterium wat gebruik word om verskillende materiaal eienskappe te filtreer, terwyl dit vergelyk word met die uitset van die modelparameters.

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This work would not have been possible without the financial support of the Anderson Lid Company (ALC) and the Foreign Affairs and International Cooperation of Italy (MAECI). I am especially indebted to my supervisor, Dr. Martin Venter, at the University of Stellenbosch, who has guided me with each aspect of the project. I am grateful to all of those with whom I have had the pleasure to work with during this project, my colleagues in Bologna who spent hours in the lab to assist me and especially my co-supervisors Dr. Matteo Minelli and Prof. Maria Grazia De Angelis at the University of Bologna, in Italy. Nobody has been more important to me in the pursuit of this project than my family and loving and supportive husband. Above all, I would like to honour God for His faithfulness throughout my life.

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Nomenclature

Constants

g = $9.81\,\mathrm{m/s^2}$

Variables

σ	Stress	[MPa]
ϵ	Strain	[ ]
E	Elastic Modulus	[MPa]
η	Viscosity	[MPa·s]
$\dot{\varepsilon}$	Strain Rate	[$\mathrm{s^{-1}}$]
t	Time	[s]
$\wp$	Permeability	[$\frac{\mathrm{cm^3}}{\mathrm{sec \times cm \times atm}}$]
D	Diffusion Coefficient	[$\frac{\mathrm{cm^3}}{\mathrm{sec}}$]
S	Solubility Constant	[$\frac{\mathrm{cm^3}}{\mathrm{atm \times cm^3}}$]
T	Temperature	[K]

Chapter 1

Introduction

1.1 Overview

In the transportation industry there are few things as devastating as spoilt cargo. Since cargo experiences a wide range of conditions, cargo should be packed and secured in a robust manner. Hence, inflatable dunnage bags are used to stabilize and secure cargo and therefore they have changed the way cargo is transported throughout the world. Most of the dunnage bags that are currently produced contain an interior airtight polyethylene (PE) bladder, which provides the inflatable property, around which a woven polypropylene (PP) cover is stitched to give the bag its strength, see Figure 1.1. Although the current double-layer dunnage bags are sufficient, the production of the current double-layer dunnage bags is time-consuming. An airtight PE bladder is manually placed inside a woven PP cover which is then stitched together. This task is repeated for each individual dunnage bag, which means that the production rate is highly dependent on the rate of the employees' stitching skills.

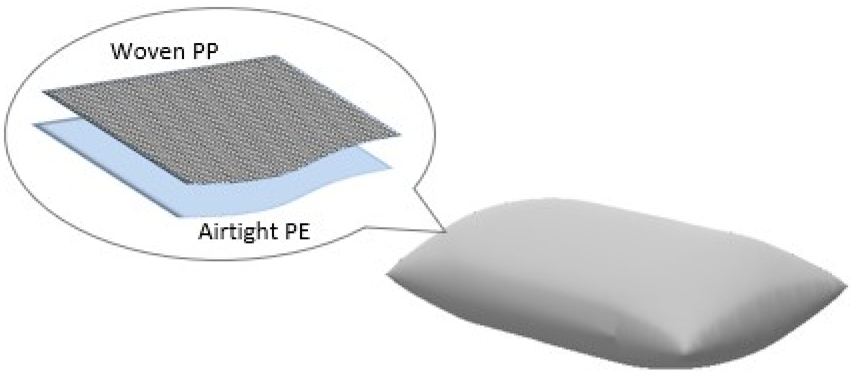


Figure 1.1: Double-layer dunnage bag

The aim of this project is to investigate a method of setting up a material criterion for the current double-layer dunnage bag. The intention of establishing a material criterion is to create boundaries within which candidate single-layer materials can be discovered. The boundaries are limits and relations of material properties that result in similar behaviour as the current double-layer dunnage bags. Physical testing of the dunnage bags and swatch material testing are required to create a material criterion. Figure 1.2 presents an illustration of how this project envisions to link the physical testing, as defined by the Association of American Railroads (AAR) regulations, to swatch material testing. The AAR provides certification for dunnage bag by performing specific large-scale experiments on the dunnage bags. The AAR focuses on the dunnage bag as a whole and not on specific material requirements. Thus, the material criterion aims to tie these two methods of testing together. Once the material criterion has been established, only swatch tests will be required to identify candidate materials that will pass the AAR tests without the need of physical testing by the AAR.

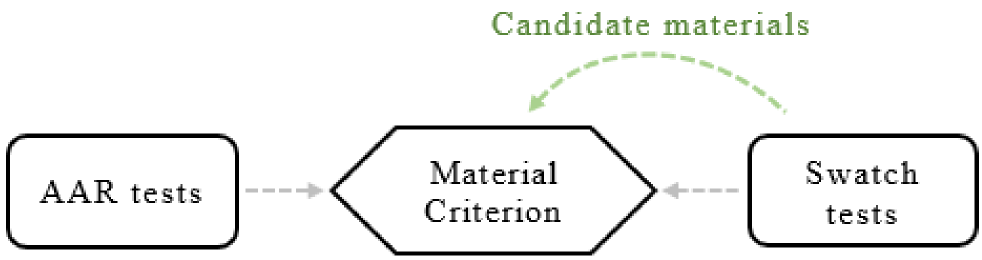


Figure 1.2: Project contribution

1.2 Motivation

The driving force behind this project is to investigate the possibility of producing an innovative product - a single-layer dunnage bag. The main criteria is to produce a dunnage bag that is more economically viable (Venter, 2016). This refers to a material that is capable of decreasing the labour time and thus increasing the rate of production.

From a business perspective, the financial contribution that this project can add to the dunnage bag industry promotes it thoroughly. Finding a viable candidate material can translate to an increase in production and thus increased profit.

The process of finding a candidate material by making use of the AAR testing alone, could be a costly option. Since it will involve sourcing numerous candidate materials, then producing full dunnage bags and then testing the full bags. The production costs alone make this route unattainable since the production occurs in two-ton batches. The material criterion makes it possible to only perform large-scale testing on the original double-layer dunnage bags and then use the material criterion as an indication of the material candidacy.

1.3 Objectives and Scope

The aim of this thesis project is to develop a material criterion based on the double-layer dunnage bag. The material criterion should be established upon experimental data such that it simulates the actual load cases of the dunnage bag. Therefore specific project objectives are stated below to amplify the success of the project:

- Research and establish a methodology upon which the material criterion can be created.
- Conduct large-scale experiments to characterize the behaviour of the current double-layer dunnage materials.
- Conduct swatch tests to determine the material properties of the current double-layer dunnage bags.
- Develop a material model that can be used as a criterion to evaluate candidate materials.
- Create mathematical models that simulate the loading conditions of the dunnage bags.
- Use the mathematical models to find possible candidate material properties.
- Communicate the results through documentation and a presentation.

Since this project involves a large range of topics, the scope of the project is defined to serve as a baseline through each section of the thesis. The scope of the project is defined as follows:

- The sourcing and development of new materials falls outside the scope.
- The range of tensile testing speeds are restricted to the ASTM recommendation.
- The primary and tertiary effects of creep fall outside the scope, only steady state creep and stress relaxation are considered.

- The woven polypropylene material accounts for the stress relaxation and creep, as it provides for the strength of the bag.
- The effects of inflating a bag are disregarded.
- The inside-layer of polyethylene accounts only for the permeation of the bag and not for the strength of the bag. This can be assumed since the polyethylene layer is created oversize as not to overload the inner layer.

Chapter 2

Background

In order to translate the problem statement of finding a viable alternative material (perhaps single-layer) for the current double layer material, there are numerous questions to be answered and techniques that can be followed to solve the problem. Accordingly, different methods to approach this multi-dimensional problem were investigated. This chapter documents the general approaches of solving interdisciplinary problems and solving open-ended questions. The material that the double-layer dunnage bag consist of add another level of complexity. Polymers display distinct material properties. Hence, research was done on the properties of polymers, with specific reference to polypropylene (PP) and polyethylene (PE).

2.1 Material Science Tetrahedron

Various interdisciplinary fields are integrated in this project. Accordingly, a standard approach that incorporates mechanical engineering, materials and processing engineering, polymer science and material science is sought that interrelates and enhances the project. The traditional material science tetrahedron (MST) is an interdisciplinary research tool that connects material science and engineering with the four areas of focus being the material structure, processing, properties and performance (Yang and Tarascon, 2012).

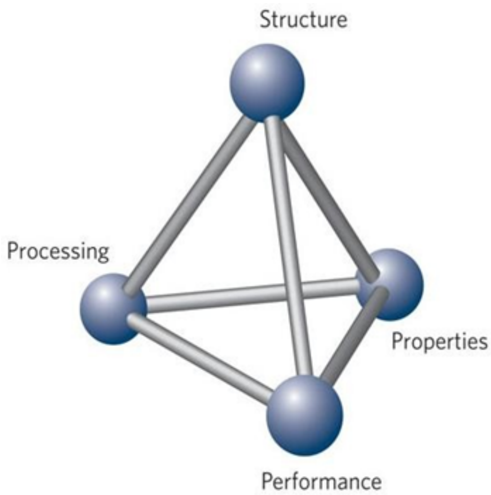


Figure 2.1: Material Science Tetrahedron(Yang and Tarascon, 2012)

Figure 2.1 illustrates a diagram of the composition of the MST. It is important to note that all four legs are connected and each aspect affects the final design of a material. The properties and performance of the material forms part of the mechanical engineering research field, whereas the structure of the material is evaluated within the polymer science field. The processing forms part of the materials and processing engineering. However, the scope of this project mainly focused on the properties and performance of the material.

Figure 2.2 presents an emerging system materials engineering triangle. Yang and Tarascon (2012) explains that the systems materials engineering triangle shows the importance of system-level planning that starts from individual components and is followed by interface optimization. It can be observed that experiments and theory support all three legs of the triangle. Thus, all the experiments performed on the dunnage bag are based on theory. Thereafter, the experimental results are compared to theory as validation. By incorporating this standard structure, a material criterion can be found. Figure 2.3 gives an illustration of the MST application to this research project and it sets the foundation to the project approach.

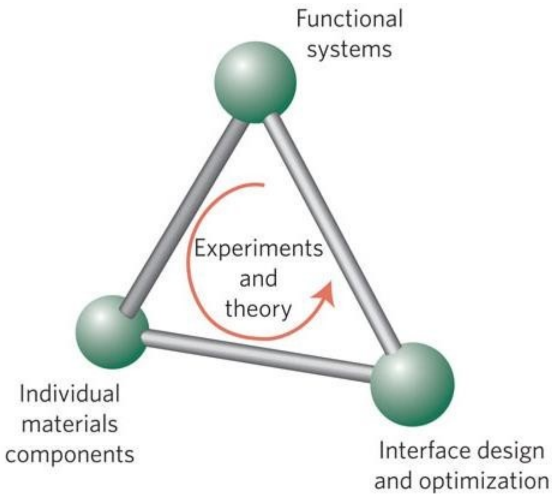


Figure 2.2: Emerging Systems Engineering Triangle (Yang and Tarascon, 2012)

The most adequate method to support the MST strategy is to create a mathematical model that combines the physical, mechanical and barrier properties. By finding mathematical relationships between the different fields, links are created that enable meaningful experiments. Furthermore, the experiments are divided into two categories, a mechanical case study analysis and laboratory analysis. The mechanical case study analysis investigates the large scale physical properties of the dunnage bags whereas the laboratory analysis inves-

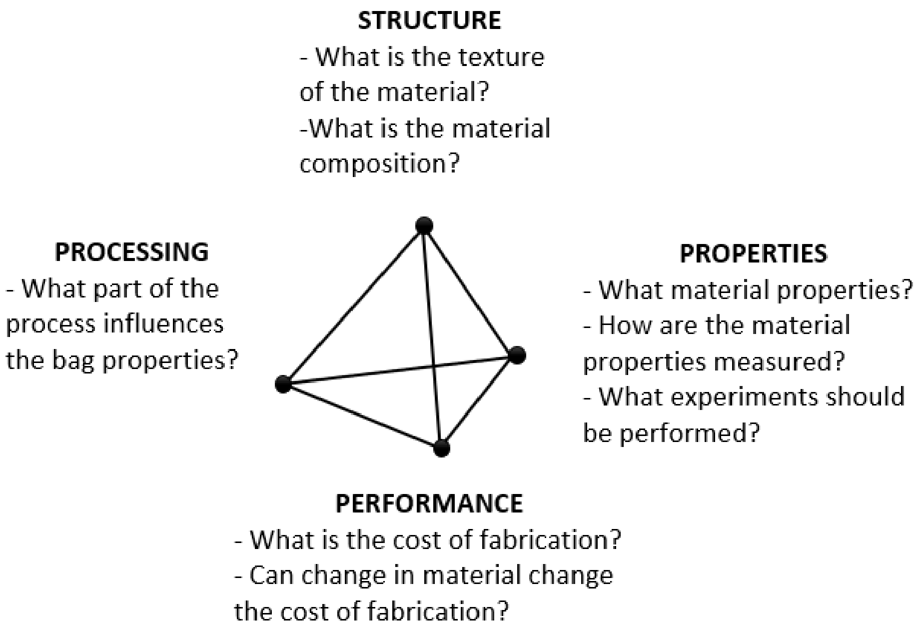


Figure 2.3: Material Science Tetrahedron applied to dunnage bag

Figure 2.4: Dunnage bag used to restrain multiple boxes in container.

tigates the material properties specifically.

2.2 Dunnage Bags and Production Processes

Background on Dunnage Bags

Dunnage can be viewed as materials that are used to keep cargo in position. When a container is loaded with cargo (For example: boxes) without filling the voids between the boxes, sudden movement during conveyance can cause the cargo to move around and become damaged. However, damage to the boxes can be prevented by placing a dunnage bag between the boxes and inflating the bag to the desired working pressure. Figure 2.4 presents an illustration of how a dunnage bag secures cargo.

Dunnage bags are normally used to fill a maximum prescribed void of 305 mm along with a maximum contact area of 3 m by 2 m. A dunnage bag consists of three major components, a compliant airtight bladder, a reinforcing cover and a non-return valve (Venter, 2015). Dunnage bags can range from level 1 to level 5. Level 1 dunnage bags are lateral void fillers and they can withstand the least pressure from all the dunnage bag levels. Whereas,

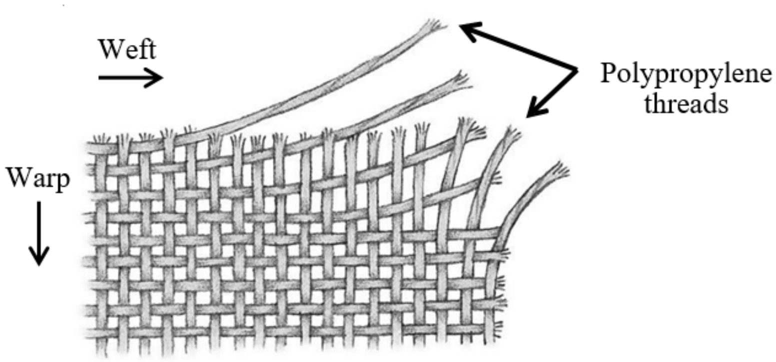


Figure 2.5: Plain weave structure of polypropylene

a level 5 bag is a lengthwise void filler and it can withstand loads of up to 92 986 kg. The scope of this project involves a level 1 bag, as requested by industry partners. A level 1 dunnage bag has a more openly-packed weave material which is not as rigidly woven as the higher level bags. Thus a sample can easily unravel if it is not handled with care. Figure 2.5 presents the plain weave structure of polypropylene whereby the orthogonal material directions are warp (the machine direction) and weft (the cross direction).

The reinforcing polypropylene cover is made from plain woven polypropylene material which is non-linear, non-homogeneous and non-continuous. This is due to the fact that the fiber architecture, matrix properties and fiber properties all affect the mechanical characteristics of the composite material (Dixit and Mali, 2013). The woven material is produced by interlacing two mutually perpendicular sets of yarns or threads. The threads that run lengthwise are named warp, while the vertical threads are called weft or fill. The pattern in which the warp and weft threads are interlaced defines which type of weave it has, in this case it is termed plain weave.

Dixit and Mali (2013) explain that woven materials are anisotropic, flexible and have distinct viscoelastic properties (Dixit and Mali, 2013). These properties indicate that the experiments may involve complex problems. In addition, Naik and Ganesh (1992) explain that the micromechanical behaviour of woven fabric laminates depends on the fabric properties, which in turn depend on the fabric structure. Various parameters are involved when determining the fabric structure, namely, weave, fabric count, fibre characteristics, fineness of yarn, yarn structure, degree of undulation, etc. Naik and Ganesh (1992) also describe the architecture of a woven fabric lamina as complex since there are numerous parameters involved when determining the mechanical and thermal properties of woven fabric (Naik and Ganesh, 1992).

Dixit and Mali (2013) identify fiber characteristics that influence the mechanical characteristics, namely, the fiber bundles, the thread spacing, the stacking sequences, the fiber orientation, the fiber architecture and the fiber volume fraction. However, Dixit and Mali (2013) also explicates that as a result of the interlacing of the fibers, woven materials offer excellent resistance to damage growth and exceptionally high values of strain at failure when in tension, compression or impact loading. Woven materials exhibit adequate dimensional stability in both the weft and warp directions, resulting in elevated out-of-plane strengths (Dixit and Mali, 2013).

Manufacturing of Polypropylene Threads

The manufacturing of a polypropylene bag involves different production operations, namely, fiber making, yarn making, weaving and manufacturing of the bag. Firstly, polypropylene resin is discharged into a hopper of an extruder and then heated to pass through a die to form a film. The film is then cooled and cut into a fixed width. The slit films are supplied continuously into equipment that stretches the slit films. A hot plate heats the slit tape film which is then stretched by high speed rollers. From this, a stretched yarn is annealed and wound on a bobbin which is delivered to weaving process. This first stage determines the tensile strength of a woven polypropylene bag (Bags, 2014).

The weaving process proceeds by weaving the stretched yarn into a tabular state. The yarn that is drawn out from a creel stand is set on a loom in a circular shape and used as a warp. When the loom is operated, a shuttle rotates in a circular motion which causes a pick to move through the warp in a circular motion causing a weaving effect. The last stage of the production process is where the woven yarn is print, cut to the desired length and transformed into a bag using cutters, printers and sewing machines (Bags, 2014).

Polyethylene Production

The polyethylene bladder is the inner layer of the dunnage bag which provides for the inflatable property. This inner layer is made from low density polyethylene (LDPE). The monomer of polyethylene is ethylene. The International Union of Pure and Applied Chemists (IUPAC) name it ethene. Ethene is a gaseous hydrocarbon with the formula C_2H_4 that can be seen as a pair of methylene groups ($=CH_2$) connected to each other as illustrated in Figure 2.6. Since the compound is highly reactive, the ethylene must be of high purity. Ethylene is a stable molecule that polymerizes only upon contact with catalysts. The conversion is highly exothermic. Polyethylene is made by using several methods of addition polymerization of ethene, which is produced by the cracking of ethane and propane, naphtha and gas oil. This is a radical polymerization process and an initiator, such as a small amount of oxygen, and an organic peroxide is used (Lazonby, 2017).

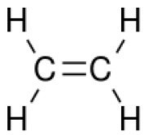


Figure 2.6: Ethylene chemical composition (Sperling, 2005)

The manufacturing process is as follows, ethene is compressed and passed into a reactor together with the initiator. The molten polyethylene is removed, extruded and then cut into granules once it solidifies. The unreacted ethene is recycled. The average polymer molecule contains 4 000 – 40 000 carbon atoms, with many short branches as illustrated in Figure 2.7. LDPE has a density of less than 0.930 $\frac{g}{cm^3}$. It has an excellent resistance to acids, bases and vegetable oils. Additionally, LDPE also has a good combination of properties for packaging applications which require heat-sealing such as toughness, flexibility and transparency.

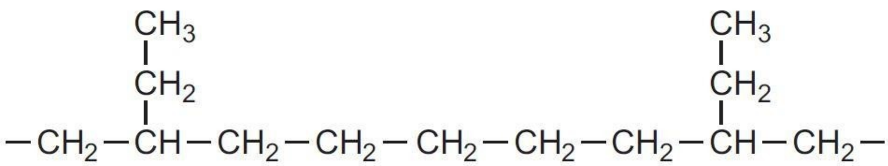


Figure 2.7: Polyethylene with small branches (Sperling, 2005)

2.3 Polymeric Material and Viscoelastic Behaviour

Sperling (2005) explains that polymers respond differently to uniaxial loading, depending on their molecular strucure. The different responses of polymers are shown in Figure 2.8.

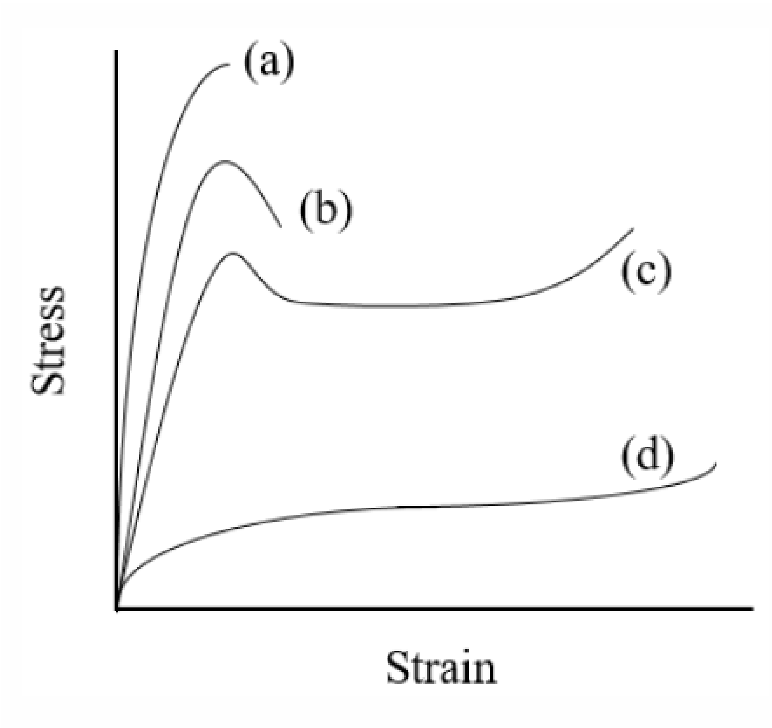


Figure 2.8: Stress Strain Behaviour of semi-crystalline polymers: Where (a.) brittle behaviour, (b.) ductile behaviour, (c.) necking and cold drawing, and (d.) rubber-like behaviour (Sperling, 2005).

An elastic material deforms linearly proportional to the stress, when a tensile stress is applied, and the material instantaneously returns to its original state after the stress is removed. A viscous material elongates when a stress is applied but it does not return to its original dimensions after the stress is released. A viscous material is both time and temperature dependent. Accordingly, a viscoelastic material is rate-dependent and the elasticity of the material changes depending on the rate of the loading. In general, when strain rate is rapid the response is mainly elastic. Whereas when the strain rate is slower, the viscous component of the material increases and the elastic response decreases. A material that exhibits both viscous and elastic properties when undergoing deformation is called a viscoelastic material. Materials with viscoelastic properties hold a relationship between stress and time-dependent strain.

Typical viscoelastic behaviour of polymers include:

- When stress is held constant, the strain will increase with time, this is defined as creep.
- When the strain is held constant, the stress will decrease with time, this

is defined as stress relaxation.

- The stiffness of a material depends on the rate of stress application.

Creep in materials can be split into three stages, Figure 2.9. In the primary stage, the strain rate decreases with time, this occur over a short period. The secondary stage has a constant strain rate. Lastly, in the tertiary stage, the strain rate increases rapidly until failure (Barrett, 2016).

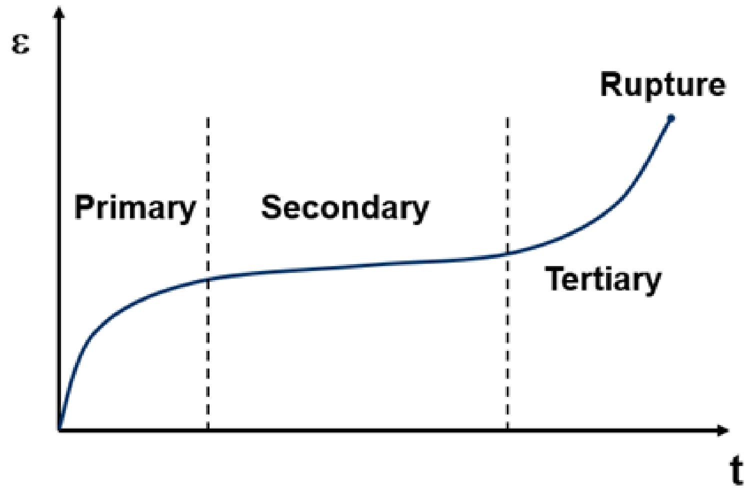


Figure 2.9: The three phases of creep in polymers (Barrett, 2016).

Hooke's law of elasticity states that the stress (σ) is proportional to the strain (ε) as seen in equation (2.3.1). This property can be illustrated by a spring, Figure 2.10.On the other hand, Newton's law of viscosity states that the stress (σ) is proportional to the strain rate ($\dot{\varepsilon}$) as seen in equation (2.3.2). This property can be illustrated by a dashpot, Figure 2.11.

$$\sigma = E\varepsilon \tag{2.3.1}$$

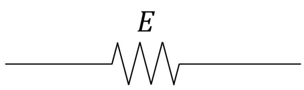


Figure 2.10: Spring

$$\sigma = \eta\dot{\varepsilon} \tag{2.3.2}$$

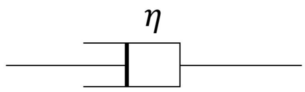


Figure 2.11: Dashpot

2.4 Constitutive Modelling

Knowing how viscoelastic material behave, the viscoelastic response can be characterized by the various equations. Roylance (2001) explains that constitutive modelling can be expressed as a method of developing mathematical simplifications of physical behaviours that are rather complex. By combining various constitutive equations, a constitutive model is formed. A constitutive equation forms a relationship between two of material's variables. This constitutive equation can then approximate the response of the material to external factors (Roylance, 2001). A constitutive equation can be combined with equations that are related to governing physical laws in order to solve an existing problem. Robert Hooke developed the first constitutive equation relating the stress exerted on a material to the material's elastic response (Lautrup, 2011).

Since the project aims to find links between swatch testing and the actual dunnage bag behaviour, it is essential to find the exact parameters from a specific curve behaviour. Thus by examining the behaviour of the material with specific attention to its elasticity and viscosity, it is possible to relate the mathematical model to various other materials without the need of testing each type of material. Furthermore, since polymers have viscoelastic behaviour, they have more than one region of elasticity, so it is essential to capture the entire behaviour of the curve. By using constitutive modelling, it is possible to input the viscosity and elasticity of a material and thus see whether a material could be suitable candidate for a single layer dunnage bag or not. The four different constitutive models include: (1) a Maxwell Model, (2) a Voigt-Kelvin Model, (3) a H-K Model and (4) a Burgers Model.

Maxwell Model

The Maxwell model consists of a linear elastic spring and a linear viscous dashpot element connected in a series, Figure 2.12 (Roylance, 2001).

$$\frac{d\varepsilon}{dt} = \frac{1}{E}\frac{d\sigma}{dt} + \frac{\sigma}{\eta} \tag{2.4.1}$$

Figure 2.12: Maxwell Model

Voigt-Kelvin Model

The Voigt-Kelvin model consists of a linear spring element and a linear dashpot element which are connected in parallel, Figure 2.13 (Roylance, 2001).

$$\sigma = \eta \frac{d\varepsilon}{dt} + E\varepsilon \tag{2.4.2}$$

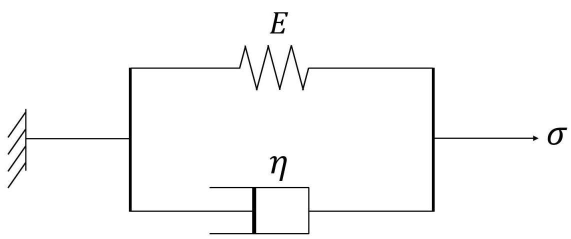


Figure 2.13: Kelvin-Voigt Model

H-K Model

The three-parameter H-K model, also known as the standard linear model, consists of a spring (E_1) coupled in series with the Maxwell model (E_2, η_2), Figure B.1 (Roylance, 2001).

$$\sigma = \frac{\varepsilon}{\left(\frac{1}{E_1} + \frac{1}{E_2}(1 - \exp(-\frac{E_2}{\eta_2}t))\right)} \tag{2.4.3}$$

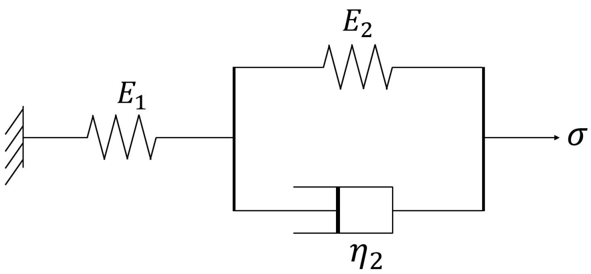


Figure 2.14: H-K Model

Burgers Model

The four-parameter Burgers model consists of two simple models, the Maxwell model (E_1, η_1) and the Voigt-Kelvin model(E_2, η_2) coupled in a series, Figure 2.15 (Roylance, 2001).

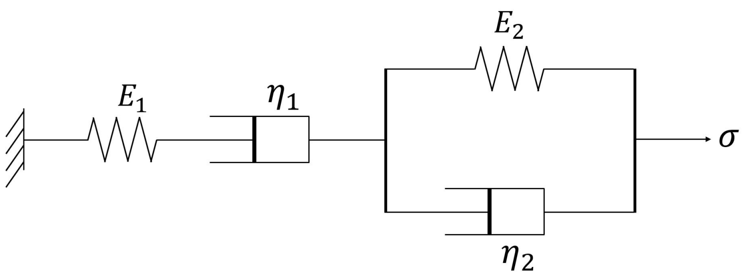


Figure 2.15: Burgers Model

$$\sigma = E_1 \varepsilon \left(1 + \frac{E_1 t}{\eta_1} + \frac{E_1}{E_2}(1 - \exp(-\frac{E_2}{\eta_2}t)) \right) \tag{2.4.4}$$

It can be observed from equation(2.4.4), that if viscosity (η_1) tends to infinity, the second term between brackets tends to zero, thus the Burgers model becomes the HK model, equation(2.4.3). This observation makes sense if the mechanics of the dashpot-spring model is considered. Should the dashpot (η_1), which is in series with the spring (E_1), become extremely viscous, the dashpot element becomes negligible and thus only the spring and the parallel connected elements influence the mechanics.

2.5 Mathematical Modelling and Model Fitting

Mazur (2006) explains in his article the value of mathematical models in experimental analysis of behaviour. He explains that mathematical models can make precise and important statements about behavioural processes that are relevant to anyone who is interested in explaining, predicting, or controlling behaviour, either in the laboratory or in applied settings (Mazur,2006).

Valavala (2008) used multi-scale constitutive modelling on polymer materials. He explains that there are no widely accepted predictive multi-scale modelling techniques to relate micro-level properties of materials to macro-scale properties. Accordingly, he considered methods that relate engineering approaches to that of physicists. The core link is to understand both the fundamental behaviour and properties of material. Additionally, Valavala (2008) studied the cause-and-effect relationships of parameters in order to establish an efficient modeling framework. Valavala (2008)'s modelling method was as follows, experiments were performed, than the data was carefully analysed, a model was created and compared to theory, then he created a simulation that was again compared to the experimental results (Valavala, 2008). Based on Valavala (2008)'s method of modelling materials, this project will also incorporate theory-based experiments and combine the results with empirical mathematical models.

(Johnson, 1997) performed a study whereby an evaluation was done on the factors that effect burst test results on plastic packages. Essentially, he aimed to find correlating parameters between burst tests and tensile tests. Three different inflation tests were performed, namely, burst tests, creep tests, creep-to-failure tests. It was observed that the inflation rate should be accurately controlled for consistent test conditions. The inflation tests were performed on rigid porous packages, therefore ASTM F2054 and ASTM F1140 standards were used (Johnson, 1997).

Venter (2015) developed numerical prototypes of inflatable dunnage bags whereby inflation testing was used to evaluate the prototypes. The Association of American Railroads (AAR) was used as the standard for the inflation tests that were performed. Three difference inflation phases were identified, namely, inflation, single cycle tests and inflation to burst tests. These tests were performed using a large hydraulic press (Venter, 2015).

In accordance with Johnson (1997)'s methodology, this project aims to find a correlation between burst testing and tensile testing which will form part of the material criterion. A mathematical model will be the foundation of the material criterion, whereby the different loading conditions will be incorporated along with the swatch test experimental data. Corresponding to Venter (2015)'s methodology, the dunnage bag inflation tests will be performed in line with the AAR standard, using a large hydraulic press. However, since the burst tests will be performed for a different application, a variation of burst tests will be performed. The aim of the inflation experiments is to determine the specific parameters required in the mathematical model. These parameters include pressure, volume, void size, stress, strain and time.

With the numerous experiments that were performed, this project involves extensive data handling, therefore a reliable method of using each set of data is required to decrease the percentage error of the material criterion model. It will be a methodological mistake to learn the parameters of a predictive function and then test the function on the same set of data. This would mean that a trained model would just repetitively predict a perfect score on a value it has seen before, but it would fail to predict any other unseen data, this is called overfitting. Therefore, machine learning is employed during the data analysis process of the project to avoid overfitting. Machine learning can be described as the process training a model on a set of data and then testing the model on a set of unseen data and then measuring the performance of the model.

The material criterion will be created on the open source programming language, Python (the Jupyter package specifically). The "scikit-learn" library provides a simplified method for applying the machine learning to the data. The train-test-split method has been employed to train the data. This method splits the data into subsets. Thus, there exists a training data set and a testing data set. Figure 2.16 illustrates the concept of the train-test-split method. The training data subsets are used to train the model. Thereafter, the testing data set is used to test the trained model. Since the testing and training data sets are two different data sets, the model has not seen the testing data set during the training. Using the unseen data set creates an unbias testing condition for the model.

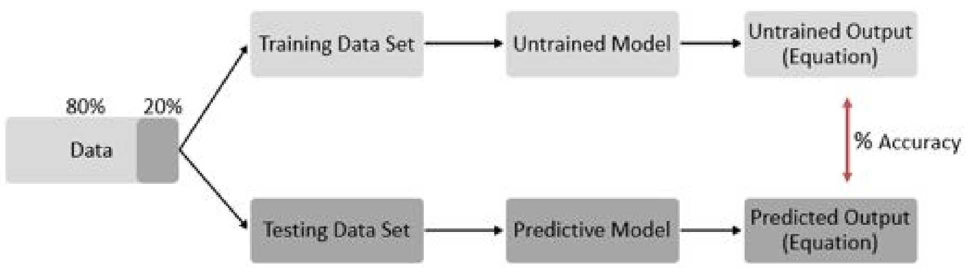


Figure 2.16: Illustration of train-test-split method

2.6 Monte Carlo Simulation

A Monte Carlo Simulation provides a method of seeing all the possible outcomes of a specific property. This simulation method is used to provide a range of possible outcomes along with the probability that it will occur. A Monte Carlo Simulation was originally used for risk analysis. This was done by building mathematical models that simulate possible scenario outcomes. The critical parameters that influence the outcome are substituted by random values, as a probability distribution. The simulation re-calculates the mathematical model iteratively, using the random number sets. Accordingly, a Monte Carlo Simulation provides a distribution of all the possible outcomes.

Woo *et al.* (2005) implemented a Monte Carlo Simulation in his study on laminated plain weave composites. He determined the effect of various orientation angles of the weave on the elastic properties. Woo *et al.* (2005) used a Monte Carlo Simulation to generate random values for thread arrangements, which occur due to shift between layers. The results of his study displayed a deviation from the average value when the weave orientation tends to an angle of zero. The method he used where as follows, 1.)He generated two random numbers (r_x and r_y) within specified limits , 2.) Then he calculated the shift between the layers Δx and Δy, where $\Delta x = r_x \times$ length and $\Delta y = r_y \times$ width, 3.) He modelled the sub-domain geometry for the specific shifts and orientation angle, 4.) Lastly, he calculated the resulting elastic properties.

In a similar fashion, the Monte Carlo Simulation will be used in the material criterion to determine how random values of the material properties influence the behaviour of the dunnage bag.

Chapter 3

Methods and Materials

With the background of the supporting literature in Chapter 2, it can be deduced that this project comprises of a wide range of fields, experiments and ideas. Accordingly, this chapter is essential in understanding the chapters to follow. This chapter serves as the essence of the thesis, since it explains how every part of the project fits together. The Research Design section describes what type of research approach was followed as well as the reasons behind why certain methods were selected. In the Research Design section, the experiments required to build the mathematical models are also selected. In the Layout of Material Criterion section, the way that the experiments and the mathematical models interconnect are discussed along with a diagram explaining the logical steps towards a completed Material Criterion. Next, the Setting and Materials section describes how the different experiments were designed and what materials were used, along with how each experiments was conducted. Then, in the Data Analysis section, the methods of how the data was processed, cleansed, evaluated and used to model the data are discussed. In this section, the constitutive modelling technique was applied to tensile data. Lastly, a summary is presented of how this chapter will be applied to the rest of the thesis.

3.1 Research Design

In the interest of designing a project with clear outcomes, the overall strategy should be chosen such that it integrates the different components of the project in a coherent manner. Accordingly, a suitable research style has been identified as a guideline for the project. A quantitative design is used to examine the relationship between variables, where the primary goal is to analyse and represent the relationship mathematically. In a scientific quantitative research approach there are four different research design styles. The different research styles are as follows: Descriptive Design, Correlational Design, Quasi-Experimental

Design and Experimental Design (Johnson and Christensen, 2008). The Descriptive Design technique describes the present status of a variable, whereby a hypothesis is only developed after the data is collected. The Correlational Design technique explores the relationships between parameters through a correlational analysis (Lappe, 2000). The idea of this design technique is to determine whether and to what degree the variables are related. On the other hand, the Quasi-Experimental Design technique explores a cause-and-effect relationship between variables. In this method, the results are compared with results not exposed to the control group variable. Lastly, the Experimental Design technique refers to the scientific method to find the cause-effect relationship between variables. In this method, the variables are all controlled except the independent variable. Therefore, a combination between the Correlational and the Experimental design techniques were chosen since this makes it possible to find correlations between parameters that have been tested experimentally. Numerous experimentation techniques (Experimental Design) were investigated to firstly identify the critical parameters, after which a parameter comparison and correlation (Correlational Design) were performed by making use of mathematical models. By using a combination of these two research design techniques, the hypothesis of this project is to determine whether there exists a candidate single layer material that correlates with the critical parameters of the original double layered dunnage bag.

Once the research techniques and the hypothesis has been identified, it is possible to integrate the inter-disciplinary parameters and concepts by making use of models. Thus, different modelling techniques were investigated to to incorporate and interrelate these concepts and parameters. There exists mainly two methods, either Finite Element Analysis (FEA) or mathematical modelling. The mathematical modelling approach enables relations to be formed between equations, load cases and variables. The mathematical models facilitate a core understanding of how specific parameters give specific output changes in the performance of the bag. On the other hand, by using a FEA simulation approach, the direct links between experimental data outputs and variable inputs are not that easily detected. Thus an empirical mathematical approach that results in a comprehensive material criterion was chosen. The mathematical models, that make up the material criterion, act as the agents to find the critical parameters of the original double layered dunnage bag. Once these critical parameters (and there output behaviour) have been identified, the candidate material search is narrowed down.

Now that it has been established that a material criterion model will be used, the various concepts and parameters have to be identified and grouped to verify which experiments have to be performed. The chosen experiments have to be based on scenarios that the original dunnage bags experience. These scenarios are best described in load cases, whereby the different load cases can

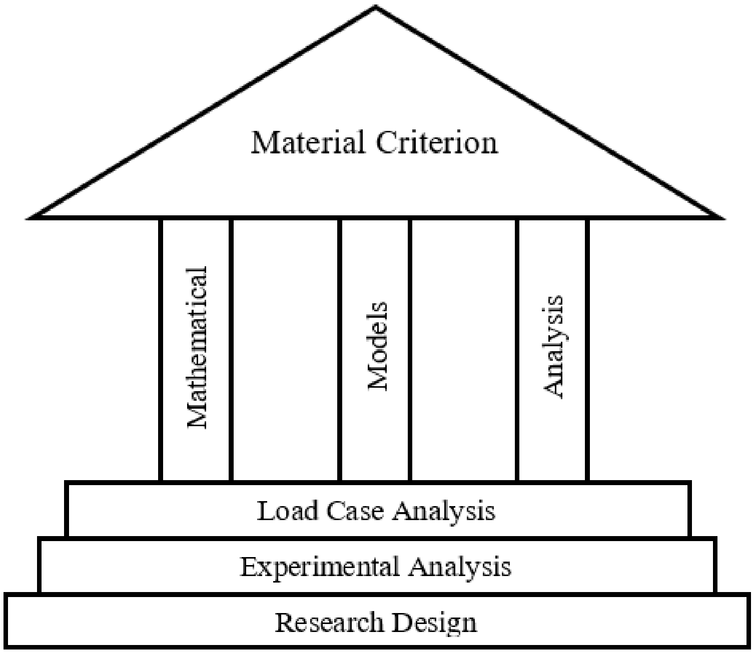


Figure 3.1: Overall structure of project

be tested. The different load cases include: (1) Inflation of the dunnage bag, (2) Cyclic Behaviour and (3) Bursting, see Chapter 5. During the inflation process, the polymer threads experience a tensile stress as the dunnage bag becomes more inflated. To test how this tensile stress influences the inflation process, the tensile behaviour of the material has to be analysed. This is done by performing tensile tests and creating a material model from the results.

Furthermore, from the time that a dunnage bag is inflated until the end of its useful lifetime, the dunnage bag looses pressure. This is due to permeation of air through the material and the stress relaxation that the polymer threads experience. Accordingly, a permeation experiment was performed see what the permeability coefficient is. On the other hand, a large-scale leak test was performed to see how the dunnage bag reacts. Figure 3.1 illustrates that the research design forms the basis of the project, since an inadequate design will cause the entire project to collapse. Then, the load cases form the second step which in-turn creates the basis for the small-scale experimentation. From the experimentation and the load case analysis, the mathematical models can be formulated, ultimately being combined to form a material criterion.

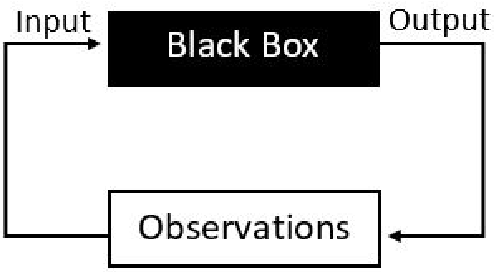


Figure 3.2: Black box approach illustraion

To formulate the mathematical models, certain inputs are required to produces a specific outputs. However, although the specific outputs may be known, the route to the outputs may be less familiar since it requires interdisciplinary parameters. Accordingly, Ljung (2001) explains the concept of a black box model as one that does not use specific prior knowledge of the physics of the relationships involved; Ljung (2001) describes it more as a process of "curve-fitting" than "modeling", see Figure 3.2. Ljung (2001) also elaborates on this concept by defining a grey box model. This is the case where there exists some physical insight, but most of the parameters still have to be determined from observed data (Ljung, 2001). More specifically, the physical insight is used to suggest combinations of the measured data signal, however the new signals are then subjected to black box model characteristics. Therefore, the main approach upon which the material criterion is built can be viewed as a black box model with certain aspects within being a grey box model. The data accumulated from the various experiments can be seen as the inputs. The data handling, curve-fitting, mathematical equations and relationships are represented by the black box, which is the parametric box of the model. The output are various models that interrelate together to simulate an actual double-layer dunnage bag. In the Material Criterion section this concept is explained more thoroughly.

3.2 Layout of Material Criterion

Overview

The material criterion is a technique of using information, such as operating conditions and material properties, related to the current dunnage bags to filter through candidate materials. The intention with the material criterion is to simulate how the bag should behave under specific load cases, using the elementary principles of various fields. These load cases are used to develop mathematical models that are made up of various equations and experimentations. This section aims to present a comprehensive layout of how each segment of the material criterion fits into the bigger picture of the project. The material criterion starts with a series of steps that convert an output idea (the resulting candidate material properties) into a conceptual model and then into a quantitative model.

As described in Chapter 2.2, the Material Science Tetrahedron (MST) and the Systems Engineering Triangle (SET) provide adequate methods of interrelating the various fields and methods of finding a single-layer candidate material. Instead of testing all the available single-layered materials available on the market, a systematic approach of setting up a criterion to find the appropriate candidate properties is followed. This is done by making use of the MST cycle, whereby theory-based experiments are performed to find an optimized solution. This solution is established upon the four legs of the MST, such that the material properties, the dunnage bag performance, its processing and the structure of the polymeric materials are intertwined in the final solution. The structure and processing of the dunnage bag will be evaluated upon the costs of the materials. The material properties are accounted for through experimentation, while the dunnage bag performance is examined by making use of the load case analysis.

Chapter 4 elaborates on the various load cases of the double-layered dunnage bag. In brief, the different scenarios that the dunnage bag might experience during a typical trip are investigated to determine how the candidate materials should perform in specific scenarios. Each load case is investigated with an experiment. With the knowledge of how the bag performs, the different segments of the material criterion model can be set up. The load cases are used as the basis for each model within the material criterion. Accordingly, each model simulates a load case, this is done by combining scientific concepts and equations, after which the results are validated by the experimental results.

Layout of Models

Each mathematical model within the material criterion is developed such that it captures an essential segment of the dunnage bag's behaviour. In most of the mathematical models, the underlying principles and equations remain the same while the algorithms vary for the different load cases. Table 6 describes the different mathematical models.

Table 3.1: Layout of Mathematical Models

Mathematical Models	Description
Constrained Inflation Model	A deflated bag is inflated to 20 kPa within a 305 mm void.
Constrained Model (Reduction in Void)	A 20 kPa inflated bag is pressed between two plates.
Permeability Model	The air permeates through the polyethylene film over time.

The constrained inflation model is constructed to evaluate the behaviour of the dunnage bag when exposed to an increase in pressure. The Reduction in Void model is developed to see how the bag reacts to compression or cyclic behaviour, when the void size is decreased. During the inflated lifetime of the dunnage bag, the air inside permeates, and the bag loses pressure. The permeability model simulates how the air permeates through the film, such that the pressure decreases due to the mass loss rate. The different temperatures also influence the amount of permeation. Accordingly, all the mathematical models are simulated on the basis of the load cases.

With reference to the black box approach explained earlier, Figure 3.3 illustrates the models within the black box that are divided into the different mechanical load cases. The load cases are applied to the current double-layer dunnage bag. The mechanics of how the bag reacts to different mechanical load cases are simulated by using the material properties found from experiments. The data that was captured during large scale testing is used to verify the model results.

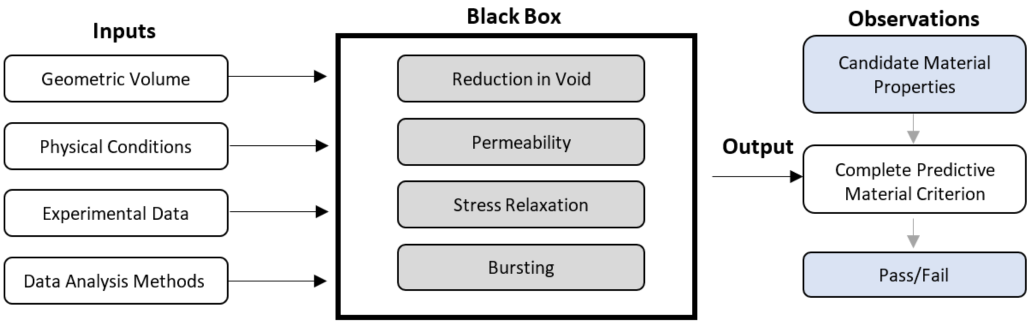


Figure 3.3: Material Criterion Layout

With the main aim of the project being to develop a material criterion for a current double-layer dunnage bag material, various aspects should be considered. As mentioned in Figure 3.1, the research design, the experimental analysis and the loading conditions are the foundation steps, upon which the mathematical models are built to support the material criterion. Therefore, in order to depict the properties and behaviour of a double-layer dunnage bag the physical conditions under which the bag operates should be determined. This refers to the different loading conditions, temperature fluctuations and pressure variations throughout a typical trip in a container. In the container, the dunnage bags experience different loading conditions, namely, rapid loading, cyclic loading and inflation. During cyclic loading or rapid loading, the void size between the boxes decreases to a certain width. With reference to Figure 3.3, the geometry of the bag can be viewed more specifically as the approximate volume due to its' shape, discussed in Chapter 6. Since the dunnage bags display distinct viscoelastic behaviour, as time and temperature changes, the properties of the bags also change. The material properties refer to the elasticity, viscosity, permeability and durability of the dunnage bag.

Figure 3.4 provides a more detailed methodological illustration of the project overview. From the three main sections in Figure 3.4, there are two routes towards the parametric model, the experimental route and the theoretical route. The experimental route includes all the experiments that have to be performed to determine the material properties and loading conditions of an actual dunnage bag. The experiments conducted include: tensile tests, permeability tests, large-scale burst tests and large-scale cyclic tests. Machine learning techniques will be employed to accurately train a model that simulates the behaviour of the PP woven threads when a tensile force is applied to it. Once the experimental results are analysed, it is fed into the parametric model as seen in Figure 3.4.

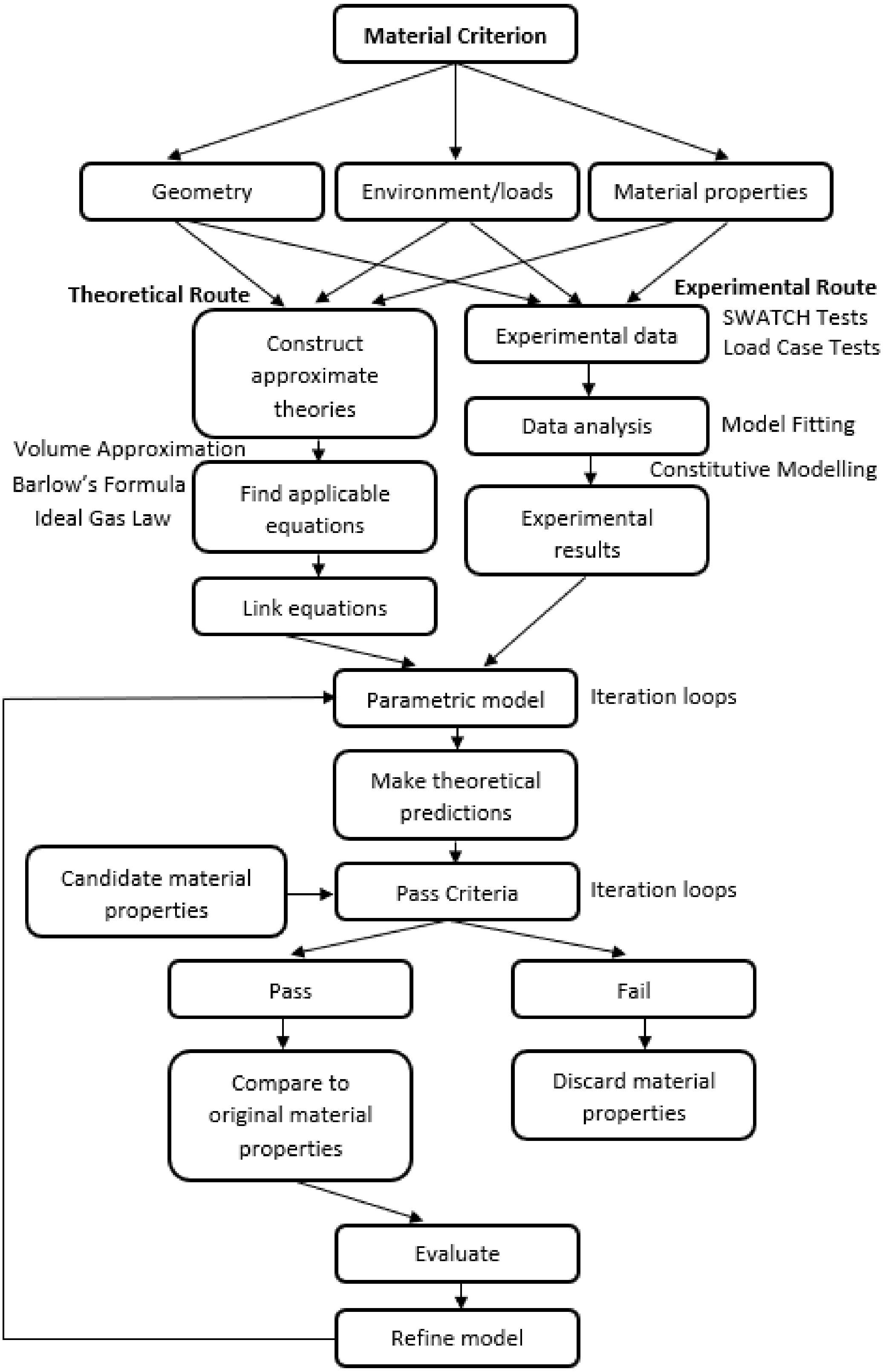


Figure 3.4: The methodological approach of the material criterion

The theoretical route starts by constructing approximate theories that simulate the viscoelastic behaviour of the PE and PP layers of the dunnage bag. The theoretical knowledge of how the material behaves dictate how the experimental data is analysed. Since the material displays viscoelastic behaviour, constitutive modelling has been employed to analyse the tensile tests' data, as explained in Chapter 2.5. From here the applicable equations should be sought and linked in order to join the theoretical route to the parametric model.

The different load cases that act on the dunnage bags during transportation sets the basis for the future of the project. From here, analytical models are built using specific state variables. For each model, assumptions are made in terms of variables that are kept constant for that specific load case. To account for these assumptions, experiments are performed and the data is fed into the specific analytical models. After all the tests have been completed, all the analytical models are combined into a predictive model. This way is it possible to test the specific properties of the dunnage bags despite the many variables and still account for the assumptions. The material criterion uses a "top-down-bottom-up" approach whereby the mathematical model is cross-validated. An assumption in one experiment is accounted for by performing another experiment that includes the "external variables" from the previous experiment. Numerous experiments were performed, the data was fed into the complete mathematical model (assuming the candidate materials will have the same geometric behaviour as the current dunnage bags) and then the two complete mathematical models were compared to indicate whether the new material is a possible candidate or not.

The parametric model combines the material models with the experimental results as well as the theoretical part of the project. In the parametric model, the initial values of the model parameters are assumed and then by iterations the actual values are calculated. The parameters include volume, pressure, mass, length, void size, stress, strain and various others. From here it is possible to make theoretical predictions. It should be restated that the material properties of the double-layer dunnage bag must be determined at this point. Then a normal distribution of these material properties, specifically the tensile moduli, are fed into the pass criteria as possible candidate properties, which can, at later stage, direct the search to the chosen candidate single-layer material. The material properties that fail in the criteria are discarded, while the succeeding properties are fed into another iteration loop. This behaviour can then be used to compare the stress-strain curves from the actual tensile tests to the stress-strain curves produced by the parametric model.

Pass criterion

The pass criterion is based on the critical parameters of the dunnage bag, such as volume, pressure and mass. If the candidate material's properties behave within the bounds of the critical parameters, it may be considered as a candidate material property. Materials whose properties behave outside the critical bounds are discarded.

3.3 Setting and Materials: Tension and Permeation

3.3.1 Tensile Tests

Polypropylene has viscoelastic properties, thus more than one tensile modulus can be determined. Since the strength-providing layer of the double-layered dunnage bag is made up of woven polypropylene threads, the process of determining the stress-strain curve is more convoluted than standard polymers. Considering that each polypropylene thread influences the result of the stress-strain curve, alternative methods of tensile testing were exploited.

The experimental objective was to analyse the mechanical properties of the woven polypropylene reinforcing cover and along with the polyethylene film. Therefore, the tensile tests were used to determine the strength, the tensile modulus and behavioural curve of the dunnage bags. Both layers of the dunnage bag were considered. However, MatWeb (2018) compares the properties of LDPE and PP, whereby the ultimate tensile strength of PP is up to four times stronger than that of LDPE. Furthermore, the moduli of elasticity of PP is more than ten times larger than that of LDPE. Accordingly, it can be assumed that the PP layer contributes the most strength and toughness of the dunnage bag and therefore only PP is considered for these properties. There are not specific standards for testing the woven polypropylene, however the crosshead speed was determined by using ASTM D882, (Properties, 1995). This standard states that for a polymer with a percentage elongation of between 20 and 100%, a crosshead speed of 50 mm/min should be used. Therefore, since the typical properties polypropylene has an elongation at break of 35% (Ridderflex), a 50 mm/min crosshead speed was used. Furthermore, the number of threads per sample was varied between 6 - 8 threads. It gave an indication as to what the role is that the number of threads play with regards to the mechanical properties of the specific samples. Appendix A elaborates on the comparison between the sample thread sizes. Single threads were tested at the same crosshead speed as the multiple thread samples with the aim to compare the stress that each thread can withstand. This way it was possible to determine the relationship between a single thread and multiple threads.

Specimen preparation

Each specimen (with multiple threads) was cut to the dimensions described in Figure 3.5. A thin strip was cut from the woven PP material, at a width of 14 threads. The threads easily unravel from the specimen, thus to account for the unravelling during the specimen preparation, 14 threads are cut initially. Then two strips (25 mm width x 160 mm length) each were cut from a tin sheet. These strips (which act as the grips) were each folded into the tin sheet (25 mm x 40 mm). Thereafter, the tin sheet was unfolded and the PP strip was then glued onto the edge of the tin sheet. From here, the PP strip was folded with the tin sheet. After which, a 100 mm gauge length was measured along with the 160 mm gripping length, as illustrated in Figure 3.5. The opposite edge of the PP strip was then cut to the exact measurements and folded as with the previous tin sheet. After the PP strip and the tin sheets were attached to each, the grips were compressed with weights of 2 kg to prevent slippage between the tin grips and the woven PP strip during testing. Lastly, the 14 threads were unravelled to the desired width (6,7 or 8 threads per sample).

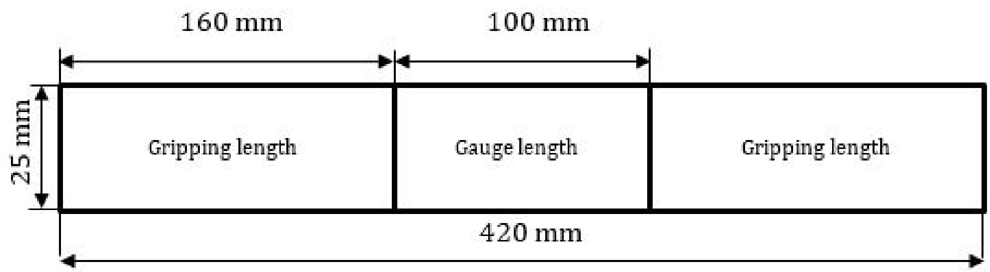


Figure 3.5: Diagram of a multiple thread PP sample before it is folded into the tin sheets. The gauge length is the area of the sample that is tested, while the gripping length is the part of the sample that is folded into the tin sheets.

Figure 3.6 presents a photograph of a polypropylene multiple-thread sample before testing. Different samples were produced for both weft and warp directions. Table 3.2 presents the exact dimensions of the multiple thread samples. For the single thread experiments, a single thread was simply unraveled (either in the weft or the warp direction) and placed between the plated grips.

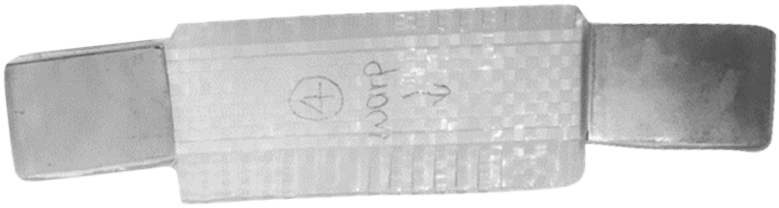


Figure 3.6: Multiple thread PP sample in the warp direction with grips of folded tin plate.

Table 3.2: Dimensions of a PP sample

Description	**Dimensions**
Gripping length	40 mm
Gage length	100 mm
Width	25 mm
Total length	180 mm
Thickness	0.042 mm.

Experimental Setup & Procedures

An INSTRON^{TM} tensile testing machine with a load cell of 50 kN, MTS grips and Bluhill acquisition software was used to perform the tensile tests. Figure 3.7 illustrates the layout of the experiment. Each test was conducted at a constant crosshead speed of 50 mm/min. For each series of tests, 7 samples were prepared and tested. The software was set up such that a 3 N pre-tension was applied to each sample. Once the 3 N tension was reached the system zeroed the load and automatically started conducting the tensile test at a 50 mm/min crosshead rate. Once the specimen fails under tension, the Bluhill software automatically stopped the INSTRON^{TM} tensile testing machine.

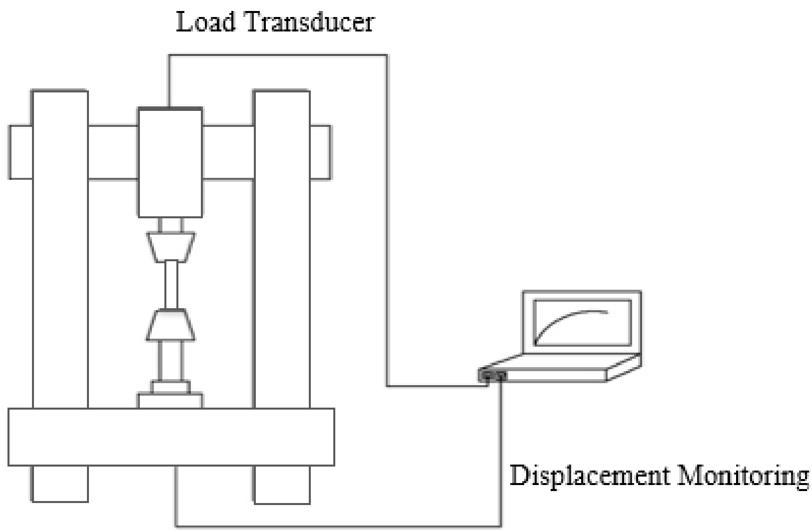


Figure 3.7: Diagram of the tensile test machine setup

In order to determine which sample set accurately describes the tensile behaviour of the PP material, the 1-, 6-, 7- and 8-thread results were compared, see Appendix A. For each specimen size, a set of at least seven specimens were tested in both weft and warp direction. The different thread-size samples (specimens with different widths) were compared since testing woven material with such an openly-packed weave presents many challenges, especially when constrained to specific gripping methods. During the tensile testing, the width of the clamps available were the limiting factor. Ideally, one would want to test a sample with the largest number of threads. Therefore, the 6-, 7- and 8-thread samples were compared to see which sample size works bests with the clamps available. The edge effects (the threads at the ends of the sample) influence the samples. Thus, for the 8-thread samples, the threads at the ends of the sample tend to unravel or snap much quicker than with the 7-thread samples since the grips were just smaller than the 8-thread sample. Therefore, the 7-thread sample was the largest number of threads that fit well with the clamp sizes available. Figure 3.8 presents a photograph of a multiple-thread test.

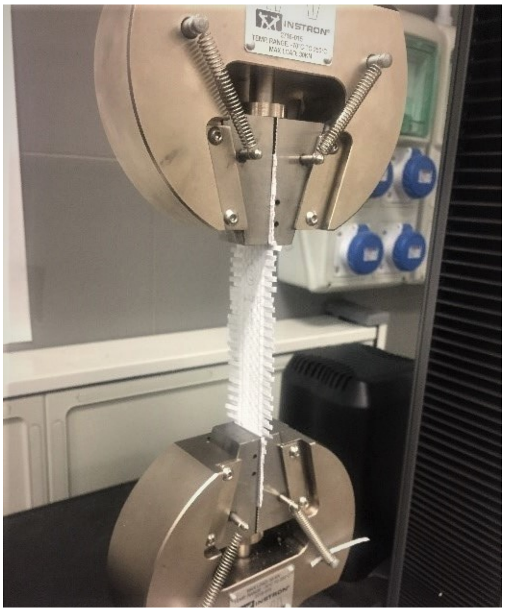


Figure 3.8: Photograph of multiple-thread sample gripped between the MTS grips

The single threads were tested using INSTRON™ Screw Side-Action Grips 2710 - 102 Series. These grips have a dual-action design, which means that the jaw faces can be adjusted independently. Figure 3.9 presents a photograph of the grips used for the single thread tests. With the dual-action design combined with flat sample holders, it is essential to ensure that the line of tensile force is precisely concentric with the grip body. In addition, the force with which the single thread sample is tightened should be such that it does not damage the sample prior to testing.

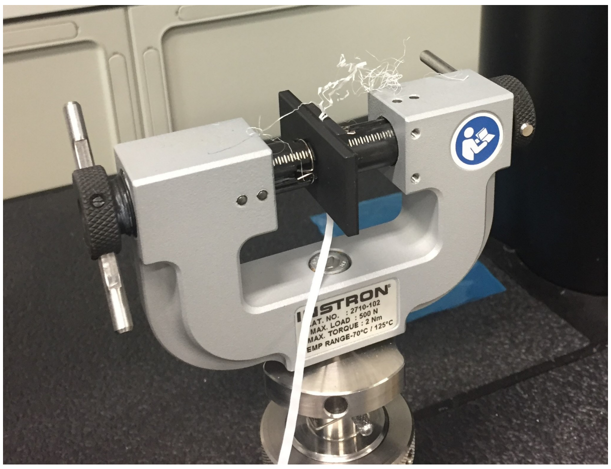


Figure 3.9: Photograph of single thread grips

3.3.2 Permeability Experiments

Permeation can be described as flow of a gas or fluid through a material. The variable of permeation does not take into account the cracks or physical flaws in the structure of the polymer (Ebnesajjad, 2003). Since the flaws in a material influence how the gas permeates through a material, it is essential that the material be fabricated carefully to avoid flaws in the polymer material. Therefore, although a specific candidate material may be selected according to a permeation criteria, the actual performance of the material may differ to what is expected since the fabrication thereof plays a major role. The permeation through polymeric membranes occurs by a solution-diffusion model. Permeability is explained by Fick's law and is defined by,

$$\wp = D \times S \tag{3.3.1}$$

where $\wp$ is the permeability of a gas $[\frac{cm^3}{sec \times cm \times atm}]$, D represents the diffusion coefficient $[\frac{cm^3}{sec}]$ and S is the solubility constant $[\frac{cm^3}{atm \times cm^3}]$. Acharya *et al.* (2004) explains that permeation occurs in three stages, namely, sorption, diffusion and desorption (Acharya *et al.*, 2004). The sorption of gas molecules occurs at the upstream side of the membrane. Owing to the concentration gradient, molecules diffuse across a membrane before they are absorbed on the downstream side of the membrane. The flux is determined by the flow rate meter, which relates to the permeability cell that measures the permeability. Accordingly, permeability is also defined by,

$$\wp = \frac{Flux \times Thickness\ of\ membrane}{Pressure\ difference} \tag{3.3.2}$$

Ebnesajjad (2003) explains that there exist several factors that affect a polymer's rate of permeation. Temperature has a significant effect on the permeation rate. As the temperature increases, the rate of permeation can increase for two reasons: 1.) at higher temperatures the solubility of a permeant will increase and 2.) the polymer chains move more abundantly which allows for easier diffusion of the permeant. The permeant is the gas of fluid that permeates through a material. The relationship between the temperature and permeation is represented by the Arrhenius-type relationship:

$$\wp = P_0 \times \exp\left(-\frac{E_p}{R \times T}\right) \tag{3.3.3}$$

where E_p is the activation energy of permeation. The activation energy can be approximated by,

$$E_p = D_e + S_e \tag{3.3.4}$$

where D_e is the activation energy for diffusion and S_e is the activation energy for solubility.

Furthermore, the rate of permeation decreases as the thickness of the material increases, this is a non-linear relationship (Ebnesajjad, 2003). At a low thickness, the permeation rate can be extremely high, while it drastically decreases as the thickness increases. For thin materials, the surface structure effects start to play a vital role in the rate of permeation. A more ordered surface will restrain the permeation to a greater extend.

The chemical characteristics of materials influence the permeation. These influential variables include the intermolecular forces like the hydrogen bonding forces and van der Waals forces, the degree of cross linking as well as the degree as crystallinity. If there exists higher intermolecular forces in the polymer, the permeation will be less since these intermolecular forces create a resistance to the development of voids between neighbouring molecules, meaning less passage way for the permeant to flow. Additionally, the degree of crystallinity dictates how orderly the structure of the polymer is. A highly order structure can at times be considered to be impermeable, since there is almost no free space for the permeant passage among the polymer chains (Ebnesajjad, 2003). It is important to note that the crystallinity of a polymer is controlled during the processing phase. Thus during the material selection for a candidate dunnage bag material, these factors and processes should be taken into consideration.

Specimen Preparation

The inner layer of the dunnage bag is polyethylene, which provides for the air-tight property of the dunnage bag. The woven polypropylene layer is highly permeable since for a level 1 dunnage bag polypropylene threads are not tightly woven. Accordingly, it is assumed that only the polyethylene influences the permeation of the dunnage bag. Standard permeation procedures with compressed air were used to test the impermeability of the dunnage bags. The permeability measurements were taken as a function of pressure and temperature. Since permeation tests are non-destructive, 3 different samples were prepared. The samples were prepared by firstly examining the polyethylene film and selecting an area that looked faultless. Then a punch-and-hammer method was used to cut out the samples to the exact size. Each sample had a diameter of 25 mm, which was standard procedure for testing polyethylene film thickness of 64 μm at the University of Bologna. One sample was used for the temperature ranges from 30°C - 60°C. For each fixed temperature, the test was performed 3 times to calculate the standard deviation and ensure accuracy.

Experimental Setup & Procedures

Figure 3.10 presents a diagram with the layout of the permeation machine. The sample is placed in the sample holder, then all the connections are closed tightly to prevent leakage. A small amount of leakage can influence the results greatly. Before testing, the reservoir tank is filled with compressed air. Between each test, the system is placed under vacuum by closing the reservoir valve, opening the downstream and the upstream valves and starting the vacuum pump. The system is left to stabilize for about 30 minutes between each test. Then to start a test, the downstream and the upstream valves are closed and the reservoir valve is opened. This allows the compressed to flow across the sample, while the flow is measured on the downstream side.

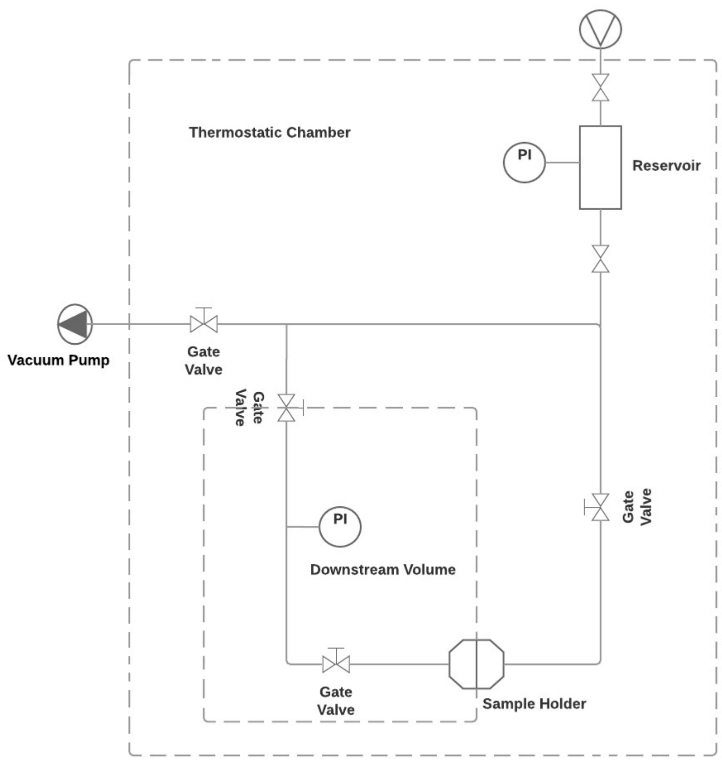


Figure 3.10: Diagram of permeation machine

Figure 3.11 presents a photograph of the permeation machine with description of where the sample holder is located as well as the import valves used during testing. Since the tests are temperature dependent, each time the temperature is changed there is a waiting periods of 4 hours to allow for the system to stabilize.

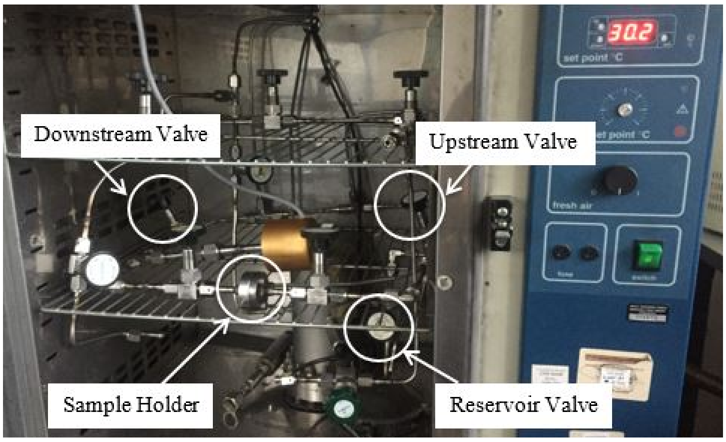


Figure 3.11: Photograph of permeation machine

Chapter 4

Experimental Results

In this chapter the experimental results found by the small-scale swatch testing are presented. The tensile tests were performed on the woven polypropylene layer, which is the layer that provides for the strength and toughness of the dunnage bag. Furthermore, the permeability tests were performed on the polyethylene film, which provides for the air-tight property of the dunnage bag. Although both layers affect the permeability and strength of the dunnage bag, determining what the ratio of each layer's contribution is to the properties may be very complex. Therefore, based on theoretical evidence discussed in Chapters 2 and 3, it will be assumed that the polypropylene provides the strength and toughness solely, while the polyethylene account exclusively for entirely for the permeability. In this chapter the various constitutive models used to fit the tensile test results will be discussed, after which the permeability results with a comparison to literature will be reviewed.

4.1 Tensile Test Results

As explained in Chapter 3.3, numerous tensile tests were performed since no standard procedure could be found for level 1 plain woven polypropylene. Therefore, the testing procedures were adapted according to the general polymer standards. This did however imply that the method of testing had to be established based on the experimental data. Accordingly, multiple thread and single thread tensile tests were performed in both the weft and warp direction. For each set of tests, at least 7 samples were tested. Therefore, approximately 60 samples were tested to generate the results listed below.

The sample width of the multi-thread samples were limited to the width of the grips available. Therefore, 6-, 7- and 8-thread samples were tested. Once all the samples were tested experimentally, the train-test-split data analysis method, as explained in Chapter 2.5, was applied to ensure accurate material modelling. Furthermore, the constitutive modelling was used to determine the curve that best fits the viscoelastic behaviour of the material. Three different constitutive models, as explained in Section 2.4, were applied to the data. With reference to that literature, the Maxwell model, the H-K model and the Burgers model were applied to the tensile test data using the train-test-split method to teach to model. An initial guess was made (the black curve), then the training data was used to teach the model and then the testing data was applied. The blue curve shows the training data while the red curve represents the trained and tested model. It can be seen in Figure 4.1 that the red curve deviates from the training data at the initial part of the curve and then the red curve tends upwards which is different from the training data. Since the Maxwell model does not have a parallel component of the spring and dashpot, it represents an oversimplified viscoelastic case. Figure 4.2 represents the HK model that consists of a spring in series with a parallel combination of spring and dashpot. This constitutive model accurately depicts the training data. The initial slope of the HK model follows the same trend as the training data and the end of the curve tends to the same slope as the training data. Lastly, Figure 4.3 shows the Burgers model that contains both a spring and dash in series as well as a second spring and dashpot in parallel. The Burgers model also simulates the training data well. However, since both the HK model and the Burgers model simulate the data well, the HK model was used in the material criterion to represent the experimental tensile behaviour, since there are fewer parameters to calibrate.

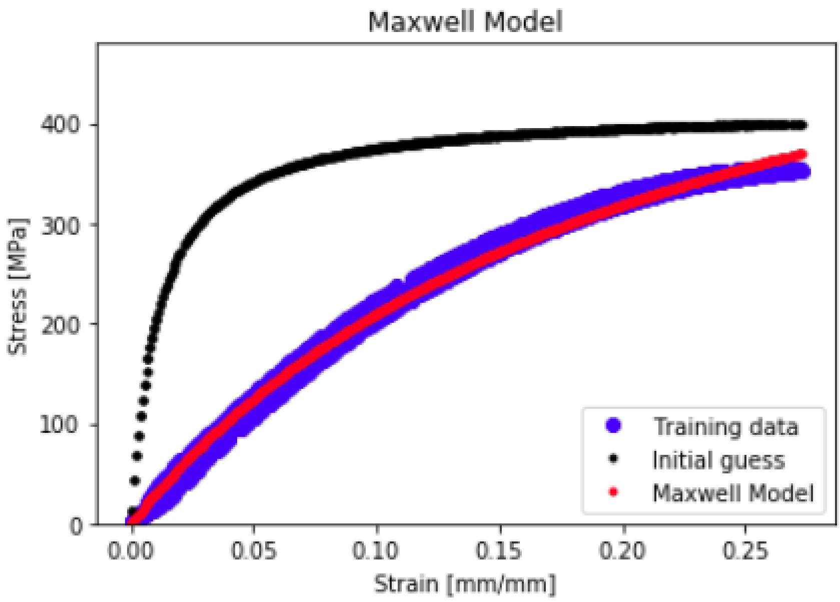


Figure 4.1: Constitutive Maxwell model

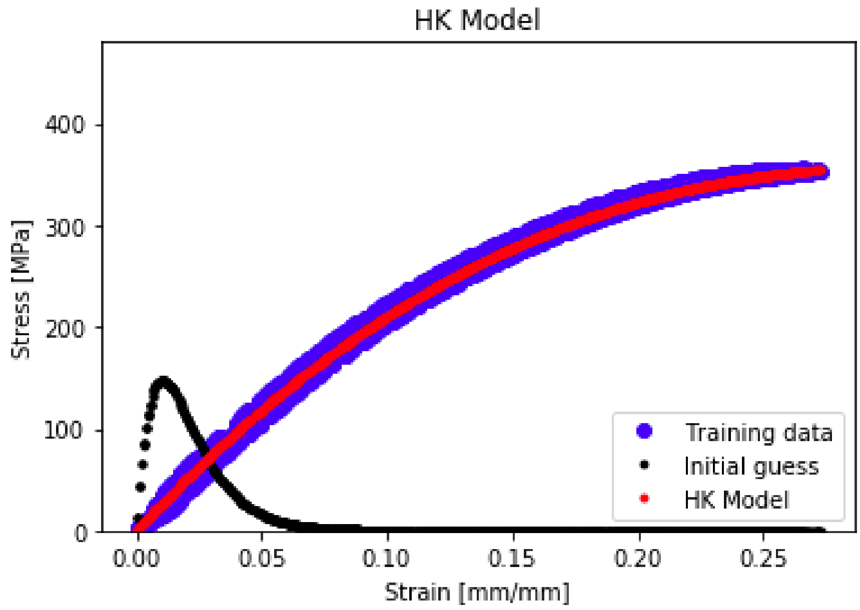


Figure 4.2: Constitutive HK model

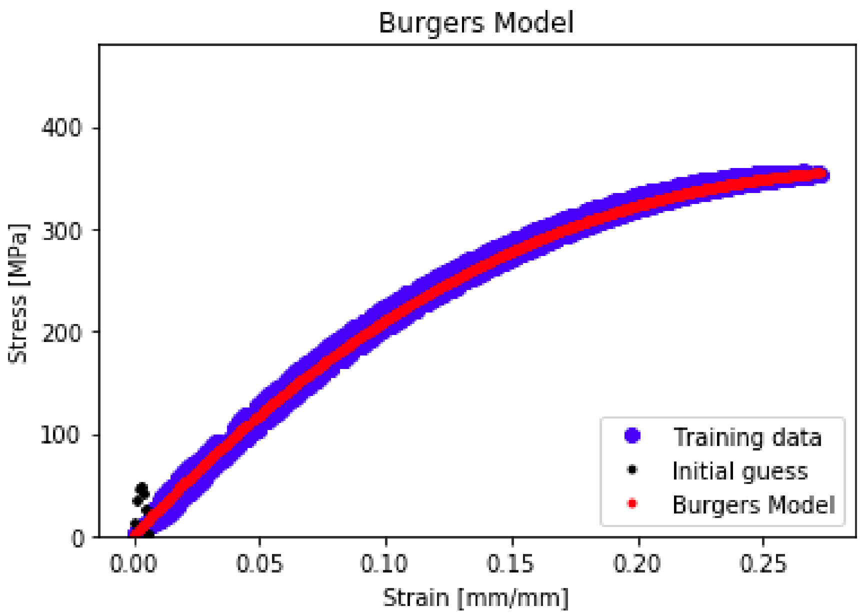


Figure 4.3: Constitutive Burgers model

The Burgers model becomes the HK model if viscosity (η_1) tends to infinity, this observation was used to test whether the models are correct. This was done by setting the viscosity (η_1) to a very large number. Accordingly, Figure 4.4 shows that the models are the same if the viscosity (η_1) tends to infinity.

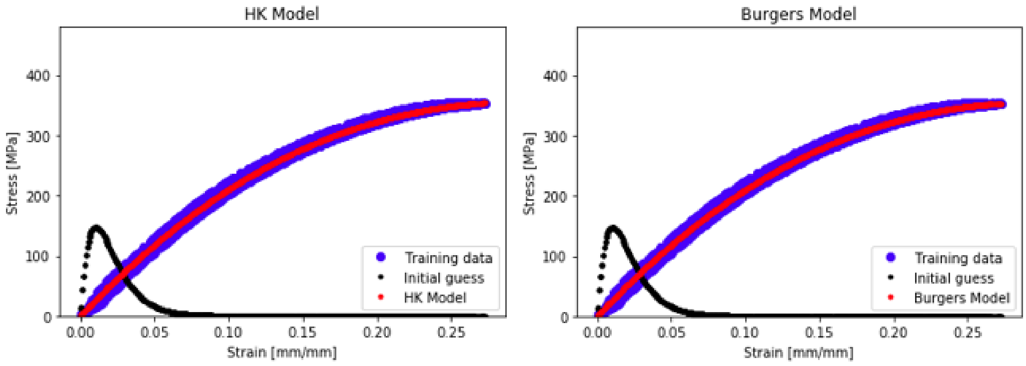


Figure 4.4: Comparison between the HK model and the Burgers model when the viscosity (η_1) tends to infinity.

With reference to choosing the correct sample size, the data processing algorithm, displayed in Appendix B, shows how the different sample sizes were evaluated. For each material property of the HK Model, the confidence interval was measured. This was done for each sample size in both the weft and the warp directions. Appendix A displays the comparison between the single and multiple threads, whereby polynomials were fitted to confirm the best size sample. Table 4.1 presents the comparison between the confidence intervals. E_1 and E_2 represent the elasticity elements and N_2 represents the viscosity element in the HK Model. It can be seen that all the samples displayed good confidence intervals, but in both weft and warp direction, the 7-thread sample displayed the best results. The 7 thread samples produced the most reliable and reproducible data, accordingly the constitutive model was applied to this specimen size.

Table 4.1: HK Model thread comparison with confidence intervals.

Number of Threads		**1**	**6**	**7**	**8**
Weft	E_1	0.993	0.995	0.995	0.995
	E_2	0.939	0.937	0.941	0.938
	N_2	0.902	0.905	0.911	0.906
Warp	E_1	0.994	0.986	0.991	0.990
	E_2	0.939	0.937	0.942	0.936
	N_2	0.905	0.877	0.897	0.888

4.2 Permeability Test Results

From the experimental procedures described in Chapter 3.3, the following permeability results were produced. Table 4.2 displays the results of the permeation tests along with the standard deviation on each set and the % error. The first test was performed at 30^{o}C. Since initial pressure on each sample does not play a significant role, the pressure varies according to the amount of compressed air in the reservoir tank. The temperature plays a significant role in the value of the permeability as revised in Equation (4.2.1).

$$\wp = P_0 \times \exp(-\frac{E_p}{R \times T}) \tag{4.2.1}$$

where E_p is the activation energy of permeation.

Table 4.2: Results of permeability tests whereby a comparison of temperature vs permeability can be observed.

Test	**Temperature [^{o}C]**	**Pressure [bar]**	**Permeability [barrer]**	**Standard Deviation**	**% Error**
1	30	1.25	1.88	0.1154	6.140
2	40	1.22	3.161	0.235	7.452
3	50	1.28	5.755	0.333	5.789
4	60	1.28	9.024	0.104	1.156

Figure 4.5 displays a permeability versus temperature graph. It shows that the permeability increases with increasing temperature. The permeability is more than four times larger at 60^{o}C than at 30^{o}C. The experimental results of the LDPE film were compared to the results as per the literature in (Massey, 2003). It is common practice that polymer materials are tested with nitrogen and oxygen seperately. Thus, finding literature where LDPE was tested with air is scare. Air is made up of 78.09% nitrogen, 20.95% oxygen, 0.93% argon and 0.04% carbon dioxide. Accordingly, the results of nitrogen and oxygen permeation through LDPE, as described by Massey (2003), were combined. This was done by taking the ratio of air to be 0.21 oxygen and 0.79 nitrogen and disregarding the contributions of argon and carbon dioxide. The difference between the experimental results and that of theory may be due to the fact that different experimental apparatus and setups were used. Furthermore, the processing of LDPE also plays a major role in the polymeric properties of the film.

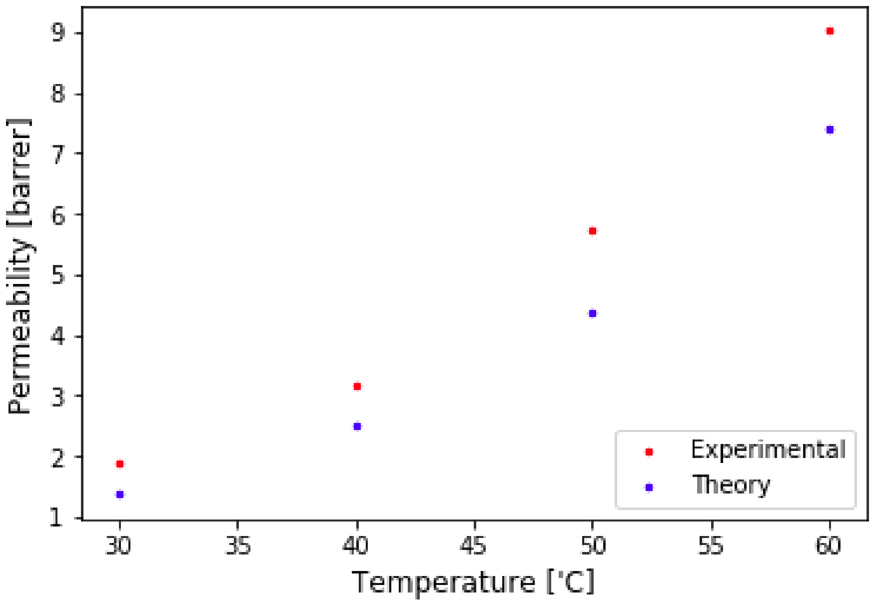


Figure 4.5: Permeability [barrer] versus Temperature [^{o}C] comparison of the experiment versus the theoretical results (Massey, 2003)

Chapter 5

Dunnage Bag Load Cases

The main function of a dunnage bag is to protect the cargo during transportation. This means that the dunnage bag should absorb the strain energy between cargo during a trip. The strain energy is mostly absorbed by the outer layer of viscoelastic material - polypropylene. The dunnage bag experiences various load cases during a typical trip. In the industry, a deflated dunnage bag is placed between two boxes at a specified void size. Then the dunnage bag is inflated to the specified pressure. During a trip, the cargo truck may drive on a bumpy road or stop suddenly. Both these scenarios can damage the cargo if the dunnage bag fails. The bumpy road can imply a cyclic loading on the dunnage bag, whereby the boxes repeatedly compress the dunnage bag and return to their original position. When the cargo truck suddenly stops, extreme forces can be exerted on the dunnage bag causing it to burst. All these different load cases are investigated during this chapter, whereby experiments that simulate the load cases are performed.

5.1 Load Cases Overview

The Association of American Railroads (AAR) has a test standard that stipulates whether a dunnage bag is safe for use. The Product Performance Profile for Pneumatic Dunnage (PPPPD) provides a confidence level for the use of dunnage bags for transportation (Association of American Railroads, 2014). There are two principal applications for pneumatic dunnage bags in transportation, namely, 1) lateral void fillers and, 2) lengthwise void fillers. The former application is where level 1 dunnage bag are used. The involved industry partner of this project requested that the area of focus be the level 1 dunnage bags. The AAR stipulates that lateral void (level 1) fillers should:

- Be capable of maintaining between 3.5 kPa and 20 kPa in voids from 101 mm to 305 mm.

- Not lose or leak significant pressure.
- Obtain the minimum burst strength of at least 55.2 kPa.

Association of American Railroads (2014) explains that prior to testing, the dunnage bags should be pre-conditioned. The pre-conditioning is required to ensure that the initial stress relaxation of the dunnage bag has occurred prior to use. Furthermore, the AAR also requires that the test fixtures for the dunnage bags (level 1 - 4) are able to test the bags at a void size of 305 mm between flat plates. The AAR defines two performance measures for the level 1 dunnage bags, 1.) a leak test and, 2) a burst test. For the leak test, ten samples are inflated to 20 kPa in a void size of 305 mm and then left for 19 days. The temperature and pressure are measured at the beginning and the end of the test. The dunnage bag should maintain a minimum 60% of its' original pressure at the end of the 19 days. Then for the burst test, five random dunnage bags from the leak test are inflated to 55 kPa in a 305 mm void size. The bag should then maintain that pressure for one minute.

From the AAR methods, it can be deduced that permeation and stress relaxation plays a vital role in the success of dunnage bag. The approximate 40% of air pressure loss during the 19 days, is due to the air permeating through the polyethylene layers and the stress relaxation of the polypropylene threads. Then according to the AAR standards, once the dunnage bag has been left inflated for the 19 days, it is inflated again to a higher pressure to see whether it will burst or not. In reality, the dunnage bag might have been in use for a smooth distant trip and then before delivery the dunnage bag experiences a sudden loading. The dunnage bag should be able to still absorb the excessive energy to protect the cargo. The AAR methods used for testing are effective to approve the use of dunnage bags, but they do not necessarily depict all the load cases of a level 1 dunnage bag during a typical trip. Accordingly, the AAR methods were used as a guideline for the load cases analyses, but with certain modifications. The main objective of the burst experiments is to act as a mechanical case study analysis. This refers to the physical conditions of the dunnage bags during operation. The different load cases that were analysed are, namely, 1) Inflation, 2) Cyclic Loading, 3) Bursting. Each of the load case experiments along with their results are explained in the sections to follow. The data processing algorithm can be found in Appendix B

Figure 5.1: Image of the double-layered dunnage bags being preconditioned prior to testing, the hydraulic press can be seen in the background.

Table 5.1: General experimental procedure for burst tests

Step	**Description**
1.	Connect and switch on the 4.8 kHz Spider and the computer.
2.	Set up the software.
3.	Test the alarm system to see that it works.
4.	Open the large gate (for the pressurized air to escape) and demarcate the entire testing area.
5.	Startup the water system.
6.	Check that all the hydraulic oil lines are closed, open the hydraulic line to the large hydraulic press and switch on pumps 1,2,3.
7.	Check that the air pipes and dunnage bag air inflator, ensure that nothing is leaking.

The experiments were performed using a hydraulic press, a Spider data acquisition system, a manometer and a thermometer. Sample preparation was required to ensure that the initial stages of stress relaxation does not have a significant influence on the tests. This is done by inflating the dunnage bags to working pressure of 0.2 bar and holding the inflated dunnage bags in the same environments as the test fixture for a minimum of 24 hours prior to testing. Figure 5.1 presents an image of the dunnage bags being preconditioned before they were tested. The standard testing procedure was followed for the experiments are described in Table 5.1.

5.2 Load Case I: Inflation

The inflation load case examines the case where the dunnage bag is inflated from zero pressure. This load case is tested to see at which point the dunnage bag will burst if the operator inflates the dunnage bag past the prescribed pressure. The candidate material should display similar properties during inflation. As the dunnage bag is inflated, the material is stretched and experiences tensile forces. Accordingly, the tensile behaviour of the dunnage bag material will be incorporated in the inflation mathematical model.

Experimental procedures & Results

Twelve dunnage bags were pre-conditioned in the same testing facility as where the experiment was conducted. The air supply line was checked prior to experimentation and the temperature was measured. The pressure was measured using a Spider 9 data acquisition system and a computer. The dunnage bag was placed inside a fenced-off section to ensure safe experimental practice. Each bag was inflated from zero pressure to burst. It can bee seen that the average burst pressure was 39 kPa, almost double the required operational pressure. The results are presented in Figure 5.2

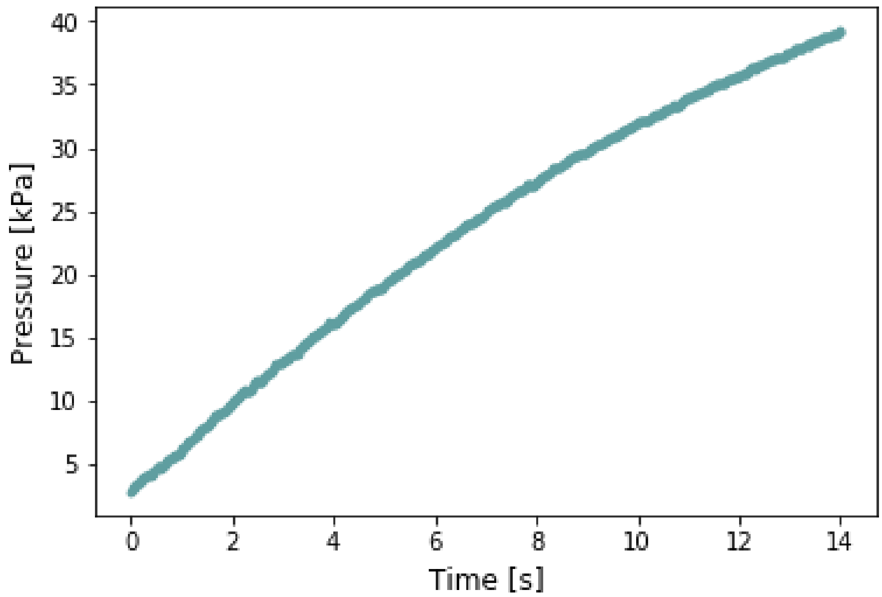


Figure 5.2: The graph shows pressure versus time for the case where the dunnage bag is inflated.

5.3 Load Case II: Cyclic Behaviour

The cyclic load case experiments were performed on level 1 dunnage bags using the preliminary procedures described in Table 5.1. Hearing protection was provided to all laboratorians and the surrounding communities were informed about the experimentation times, since the experiments could cause severe hearing damage. Thirteen preconditioned dunnage bags were tested for this load case. During the actual use of the dunnage bags in cargo, the bags are also preconditioned to account for the initial effects of stress relaxation. This is done by inflating the dunnage bags to working pressure, then after one hour the bags are inflated again to working pressure. It is necessary to inflate the dunnage bag to working pressure again since stress relaxation (and permeation) occurs. Therefore, the initial effects of stress-relaxation are regarded as beyond the scope of this project and thus the rate dependent effects on the material is discarded. Instead, the actual cyclic loading on the dunnage bag was being examined. The Spider 8 data acquisition system was again used to capture the pressure, void size and time. The hydraulic press was used to cycle between a void size of 305 mm and 200 mm. 10 cycles between the afore-mentioned void sizes were imposed on the dunnage bag, after which the plate was lowered until the dunnage bag burst. Although the dunnage bag may experience numerous cyclic loadings during a typical trip, the effects of a single cycle is considered for the material criterion. For the case of the material criterion, it is assumed that after a single cycle, the material experiences no further plastic deformation in the following cycles. Figure 5.3 shows the results of the pressure versus time for a single cycle, while Figure 5.4 presents the void size vs time. Furthermore, the pressure versus the void size for a single cyclic is shown in Figure 5.5.

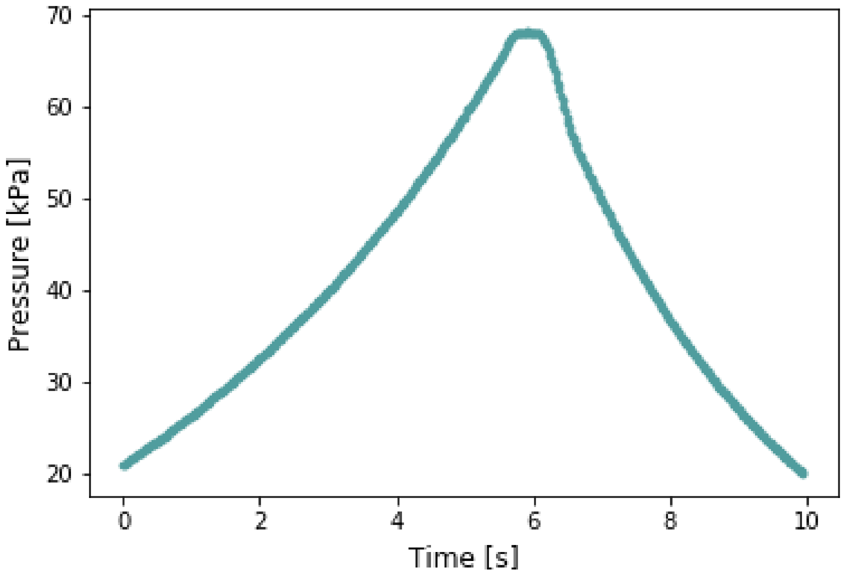


Figure 5.3: The graph shows pressure versus time for a single cycle, where the hydraulic plates lower to a 200 mm void from its' starting position of 305 mm

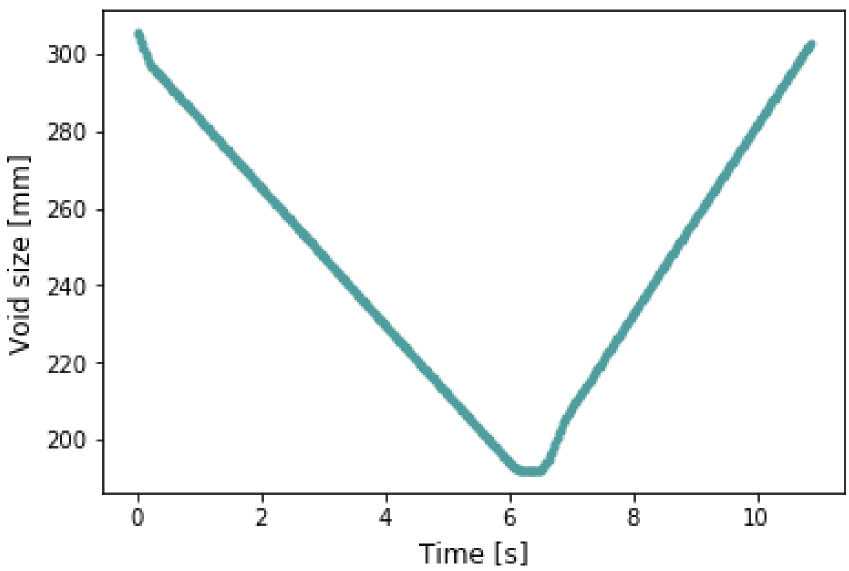


Figure 5.4: The graph shows void size versus time to simulate the cyclic loading implied on the dunnage bag during transportation.

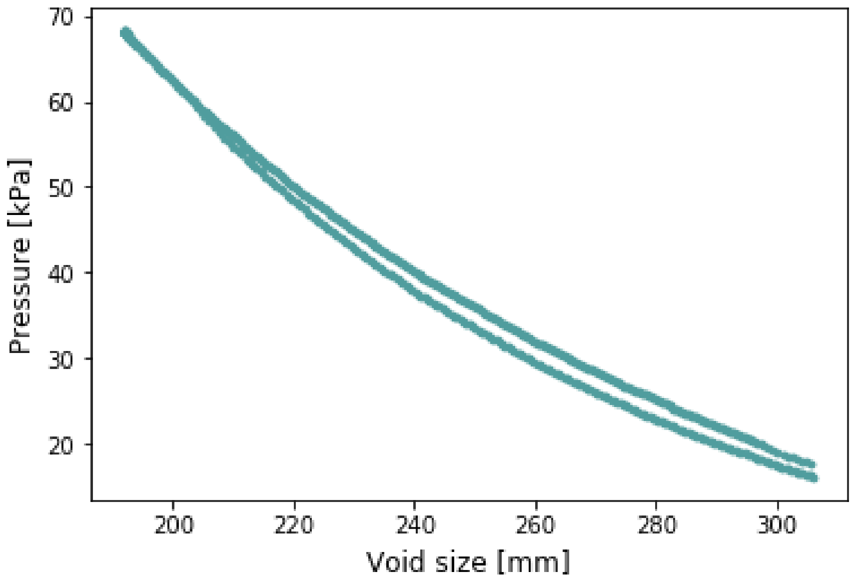


Figure 5.5: The graph shows pressure versus void size for a single cycle, where the hydraulic plates lower goes from a 305 mm void size to a 200 mm void size and back then again.

The stress-strain relations for a constrained dunnage bag can be deduced from the single cycle results and the constrained model, explained in Section 6.2. However, when observing the multiple cyclic results, seen in Figure 5.6, it can be seen that the pressure in the dunnage bag reduces as the dunnage bag is cycled. This is observed despite the fact that the void size reductions are kept constant, as seen in Figure 5.7. This phenomenon can be ascribed to the fact that the material experiences stress relaxation and creep. The dunnage bags are preconditioned to 20 kPa, however when the bag goes to a higher stress state, the dunnage bag again goes into the primary phase of creep (where it has not been preconditioned). Figure 5.6 shows a decay in pressure since the creep is dependent on stress. Once the bag has gone through the primary phase of creep, it enters into the steady state creep where it does not decrease as much. Accordingly, this can be identified as an area of further research to improve the accuracy of the material criterion.

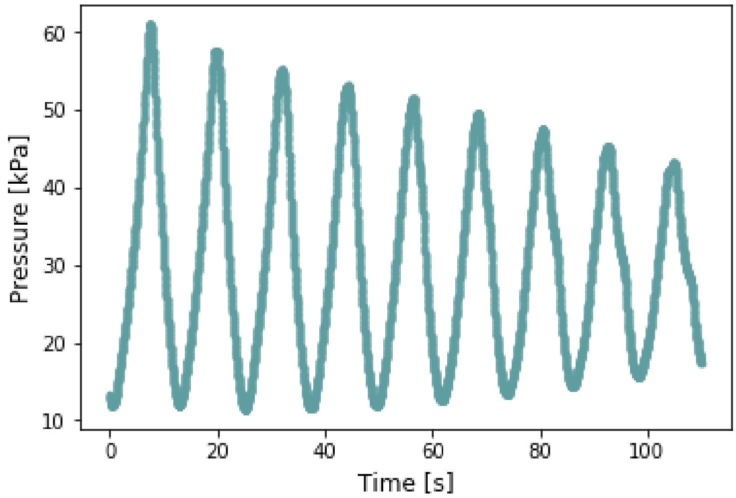


Figure 5.6: The graph shows pressure versus time where cyclic loading is imposed on the dunnage bag.

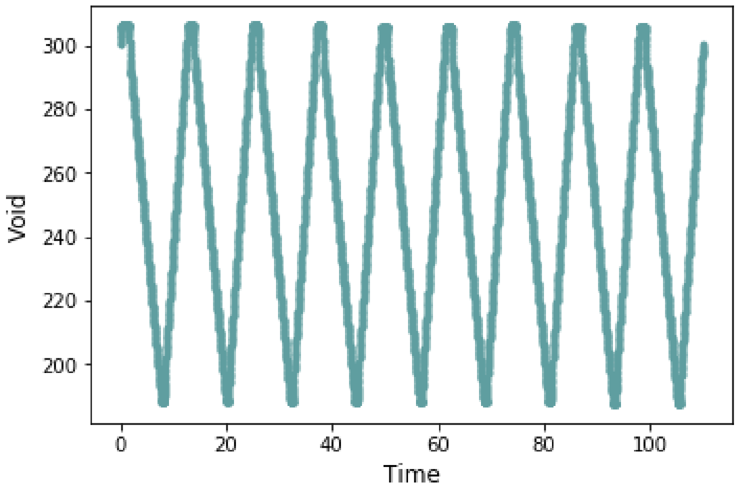


Figure 5.7: The graph shows void size versus time where cyclic loading is applied to the dunnage bag

5.4 Load Case III: Bursting

The bursting load case simulates the case where the dunnage bag is compressed between two boxes that presses the dunnage bag beyond its operating pressure up to the point where the dunnage bag bursts. The more compression force the dunnage bag can withstand, the better protection it can provide for the cargo.

Experimental procedures & Results

To simulate the bursting load case, the dunnage bag was inflated to 20 kPa and placed between the hydraulic plates that were 305 mm apart, which is prescribed void size between the boxes in a container. The steps mentioned in Table 5.1 were followed. Then after the preparation procedures were completed, the top plate was lowered by the hydrualic press, decreasing the void size until the bag burst. Figure 5.8 illustrates the results of the burst tests. It can be observed that the burst pressure was 90 kPa.

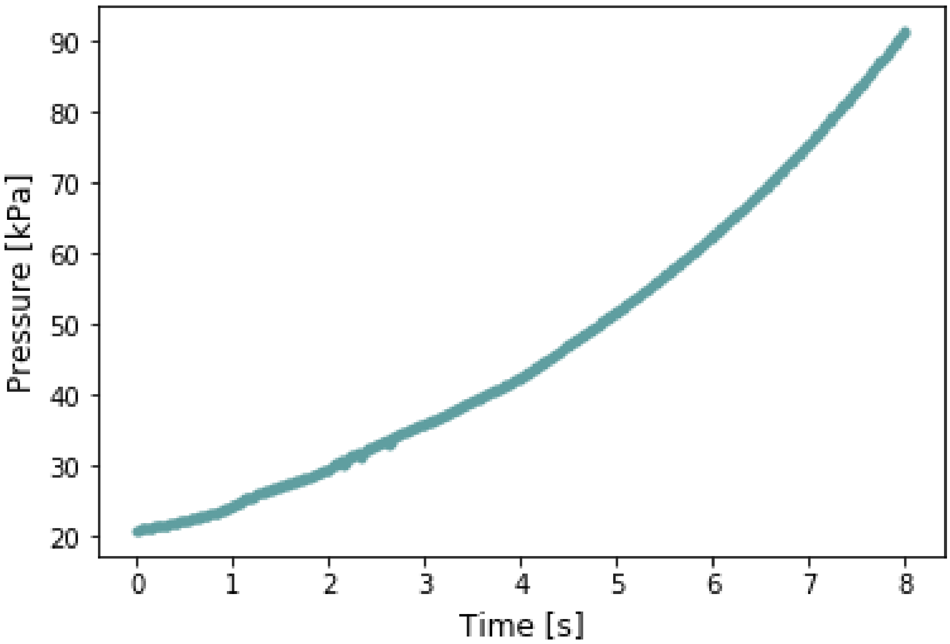


Figure 5.8: The graph shows pressure versus time, where the dunnage bag is compressed up to burst.

Figure 5.8 shows the compression bursting case (fixed mass), where Figure 5.2 shows the unconstrained inflation case (increase in mass). The burst pressure of the inflation bursting test is much lower than that of the compression bursting. The shape and the constraints on the dunnage bag play a role. During the compression burst testing, it was found that most of the bags burst at the seam or the valve. There were much greater stress concentrations on the edges, whereas with the inflation burst the stress was more evenly spread. For the inflation case, the bag bursts due to material failure in the middle of the bag. Figure 5.9 shows a model of a dunnage bag developed by Venter (2011), whereby the unconstrained inflated bag exhibits high stress concentrations near the center of the inflated bag, along the fold edges and at the valve. For the unconstrained inflation case, the material fails due to too high stress concentrations in the material. Barlow's formula presents a relationship between the radius of curvature and the pressure:

$$P = \frac{2\sigma t}{D} \tag{5.4.1}$$

where P is pressure, σ is stress, t is thickness and D is diameter.

From Barlow's formula, it becomes clear why the inflation tests exhibit a lower pressure, this is because the radius of curvature is much bigger than that of the compression bursting case. With compression bursting, the bag fails at the seams or at the valve. This is an indication that the bag does not fail due to material failure. Figure 5.10 shows that the stress concentration is more evenly distributed along the center of the bag, with the stress concentration being more prominent at the valve.

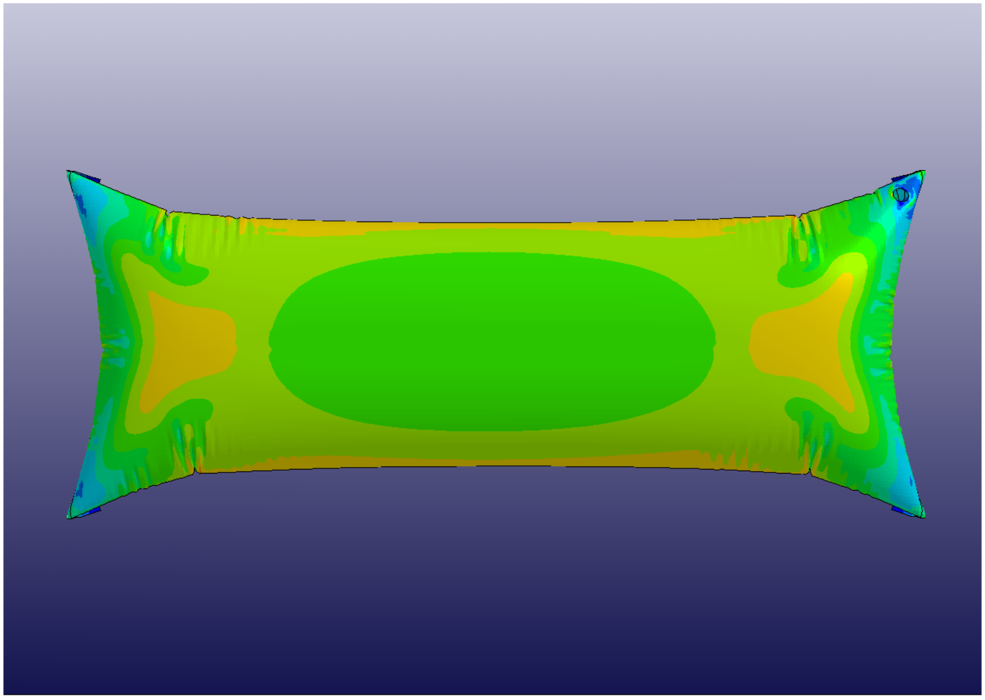


Figure 5.9: An unconstrained dunnage bag with stress concentrations near the center of the bag, where red is a high and blue is a low stress (Venter, 2011).

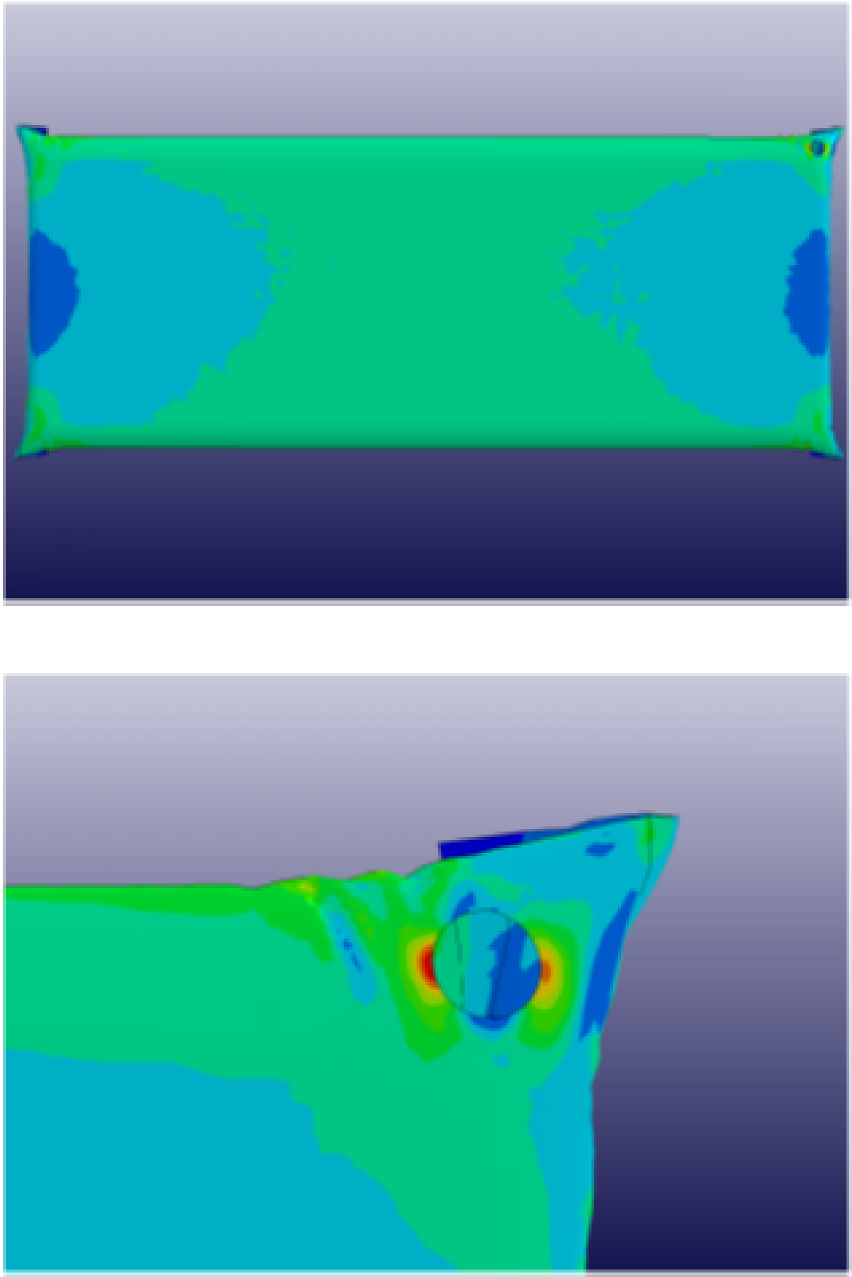


Figure 5.10: A constrained dunnage bag with prominent stress concentrations at the valve, where red is a high and blue is a low stress (Venter, 2011).

Chapter 6

Mathematical Modelling

The double-layer dunnage bags have been tested according to the various load cases documented in Chapter 5 along with the material testing described in Chapter 3 and 4. These experiments have set the basis upon which the mathematical models can be built. As explained in Chapter 3.2, the layout of the material criterion interrelates the various load cases and experiments, with the goal of setting up a criterion that evaluates candidate material properties. The process of finding the applicable equations and relations for each load case in the mathematical models have been a trial-and-error approach. In order to create separate models that simulate different load cases, various assumptions had to be made. These assumptions, along with how each mathematical model functions, are described in this chapter. Lastly, the models are verified by comparing the mathematical model outputs to that of the load cases.

6.1 Constrained Inflation Model

The basis for each mathematical model within the material criterion is an inflated dunnage bag within a 305 mm void. Therefore, this section investigates the inflation process of the dunnage bag. During inflation, the polypropylene material experiences strain. Thus, an experimental analysis and a parametric model are used to depict the inflation-like behaviour. The stress-strain behaviour of the polypropylene threads have been determined by the constitutive model, as discussed in Chapter 4.1. These insights along with the volume approximation of the dunnage bag are used to develop the constrained inflation model. The effects of inflation from an initially flat bag to a inflated bag are out of the scope of this project.

6.1.1 Volume Approximation

The volume approximation of the dunnage bag is the process of finding the approximate volume of the dunnage bag, based on the findings of researchers and a trial-and-error approach. Pak (2006) investigates the metric geometry of convex surfaces and proves that all polyhedral surfaces in R^3 have volume-increasing isometric deformations. In simple terms, the volume of the combined inflating surfaces are determined by making use of theorems and proving them. In these theorems, shrinkage and bending are accounted for in the polyhedral surfaces. By determining the mathematical relationships of specific polyhedral surfaces and implying bends, crimping or shrinkage to them, they arrive at the volume of an inflated polyhedra. A polyhedra can be described as a solid with many plane faces. An example of a polyhedra is the shape of a cushion pillow. Pak (2006) describes the wrinkling ratio and explains that the wrinkles in an pillow-shaped inflated volume should become smaller closer to the center.

Gammel (2003) performs various computer simulation experiments on the shape of a pillow (Gammel, 2003). Figure 6.1 and Figure 6.2 shows the simulations whereby the former is the intermediate shape during inflation and the latter is the final shape of the pillow. Gammel (2003) investigated various methods of determining the maximum volume of a pillow or tea bag shape.

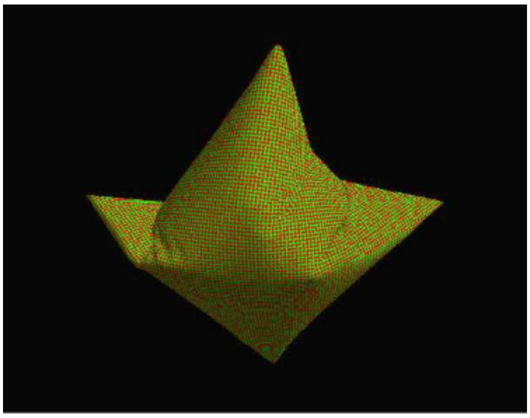


Figure 6.1: The tea bag simulation during the intermediate phase of inflation where there exists wrinkling (Gammel, 2003).

On the other hand, Robin (2004) reported on the physical experiments and the empirical formula for the volume of the a rectangular pillow. He developed an approximate formula to calculate the maximum possible inflated volume of a sealed rectangular bag, as seen in Equation 6.1.1 (Robin, 2004). This is known as the "Paper Bag Problem" or the "Teabag Problem". The Paper

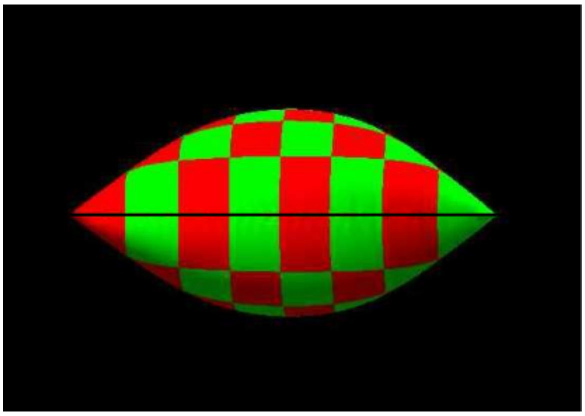


Figure 6.2: The tea bag simulation illustrating the final shape (Gammel, 2003).

Bag Problem is used to calculate the maximum possible inflated volume of an initially flat sealed rectangular bag which has the same shape as a cushion or pillow.

$$V = w^3 \frac{h}{\pi w} - 0.142 \left(1 - 10^{\frac{h}{w}}\right) \tag{6.1.1}$$

where V is volume, w is width and h is height.

Accordingly, to develop a model that accurately describes the double-layer dunnage bag, it is essential to determine the volume of the bag mathematically. Since the mathematical models follow an empirical approach, the volume of the dunnage bag will be estimated on the final shape of the inflated dunnage bag, discarding the effects of wrinkling. Using the input from the authors above and deducing that the dunnage bag have the approximate shape of a pillow, the corners of the bag has the approximate shape of a cuboid (a rectangular prism) in the centre and four cones at the corners of the cuboid. Various combinations of shapes were tested to find a "shaped-combined" volume approximation that simulates the real volume of the dunnage bag.

Robin's equation (Equation 6.1.1) was incorporated in the model and the results were compared to that of the "shape-combined" volume formula. There was a 8% error between Robin's formula and the "shape-combined" volume formula. The reason for using an alternative volume formula to that of the Teabag Problem is because the void size (diameter) is required during later calculations of the combined material criterion, while the Teabag Problem only accounts for width and length.

6.1.2 Barlow's Formula

Once the volume of the dunnage bag has been approximated, the other parameters should be determined. Barlow's formula is usually used to predict burst in a thin-walled cylinder. It is assumed that the dunnage bag is a thin-walled pressure vessel and Barlow's formula can thus be used to determine the stress of the bag, if the internal pressure, the thickness and the radius of curvature of the vessel are known. Accordingly, it can be assumed that the dunnage bag behaves like a thin-walled pressure vessel since the thickness of the polypropylene and the polyethylene layers are insignificant. Equally, the dunnage bag can within a large amount of pressure. The formula for determining whether a system is valid for Barlow's Formula is described in Equation 6.1.2.

$$t/R << 1 \tag{6.1.2}$$

where t is the thickness of a material and R is the radius of the pressure vessel. Hence, Barlow's formula provides a method of relating the pressure inside the dunnage bag to the stress of the material and diameter. The diameter is assumed to be the void size between the freight boxes. This formula enables the model to link the small-scale tensile tests (Chapter 4) with the experimental load cases described in Chapter 5. By combining the different experimental methods, it creates an opportunity to cross validate the experimental results with the model results. Equation 6.1.3 presents Barlow's formula.

$$P = \frac{2\sigma t}{D} \tag{6.1.3}$$

where P is pressure, σ is stress, t is thickness and D is diameter.

Although Barlow's formula may be an oversimplification of the problem, a similar principle has been used in a related application, whereby Venter (2015) developed a methodology for numerical prototyping of dunnage bags.Venter (2015) used the relationship in Equation 6.1.4 to relate the stress, the radius of curvature and the pressure to each other.

$$p \propto \frac{\sigma_x}{r_x} + \frac{\sigma_y}{r_y} \tag{6.1.4}$$

6.1.3 Model Assumptions

Although the stress in the middle of the bag is not consistent with the stress on the edges of the bag, it is assumed that the strain along the thread of the dunnage bag is constant across its length. This assumption is made along with the assumption of idealized dunnage bag geometry. This makes it possible to incorporate Barlow's formula. For the model, the worst-case scenario is used. Thus if all the threads of the entire bag strains the same amount (in the weft and warp direction), the bag will be modelled more "stretched out" than what it is in reality, resulting in a lower pressure than the actual pressure.

6.1.4 Inflation Model Layout

The inflation model provides a starting point for simulating the double-layer dunnage bag mathematically. Roughly calibrated initial conditions of the model are used and then calculated using the different functions in the model. This is done by making use of the known variables, such as the standard operating pressure of a level 1 dunnage bag that is 20 kPa and the dimensions of a deflated dunnage bag. The Ideal Gas Law is valid for gases that operate at Standard Ambient Temperature and Pressure (SATP). Therefore, the air inside the dunnage bag can be assumed to be an ideal gas, since it operates at approximately 23^o C and a relatively low absolute pressure of 1.2 bar, which is close to the SATP conditions. Accordingly, the pressure inside the bag is calculated using the Ideal Gas Law. From the initial parameter values, new initial values are calculated by making use of the Ideal Gas Law, the volume approximation calculation, the constitutive model of stress versus strain and Barlow's formula. This first part of the inflation model involves using the tensile behaviour of the actual dunnage bag. This is done by incorporating the constitutive model determined in Chapter 4.1. The constitutive equation is used to calculate the strain of the bag, which is in relation to the stress and the material properties. The volume of the dunnage bag is related to the strain since the dimensions of the dunnage bag change when strain is applied. Strain can be defined as the response of a material to an applied stress, this response leads to a change in the dimensions. The response of a material refers to the deformation that occurs. The dunnage bag deforms when a stress is applied to it by changing dimensions. All the equations are linked to produce the constrained inflation output of the critical model parameters (pressure, volume, length, width, stress, strain, etc). Table 6.1 presents a layout of the critical parameters along with the formulas used to calculate the parameters.

Table 6.1: A Table showing the critical parameters used in the inflation model along with the formulas used to calculate them.

Critical Parameters	**Formula**
Pressure $[kPa]$	Ideal Gas Law
Stress $[MPa]$	Barlow's Formula
Strain	HK Constitutive Model
Length $[m]$	Strain Formula
Width $[m]$	Strain Formula
Volume $[m^3]$	Volume Approximation

With reference to Table 6.1, the pressure is calculated using the Ideal Gas Law, while the stress is calculated using Barlow's formula. From the calculated stress, the strain can be calculated using the H-K Model that fits the data of the tensile tests, as explained in Chapter 5. From here, the length and width of the bag is updated, as it is related to the strain of the bag. Once the new bag dimensions are known, the volume can be calculated using the volume approximation.

6.2 Reduction-In-Void Model

The Reduction-In-Void Model simulates the load case where the dunnage bag is constrained between freight boxes, as examined in the cyclic load case, Chapter 5.3. The cyclic behaviour alternates between 305 mm and 180 mm in void size. This model refers to the case where the dunnage bag is placed between boxes in a container and inflated to 20 kPa. Thus the model starts by calling the function "reset2Inflation". This function resets all the initial parameters to that of the constrained inflation case. During a typical bumpy trip, the boxes compress the dunnage bag. Therefore, it is essential to ensure that the candidate materials for the dunnage bag are able to withstand the compressive forces in a similar fashion as the original double-layer dunnage bag. Although the cyclic load case examined the effects of cyclic loading on the dunnage bag, a single reduction in void size of the dunnage bag is modelled mathematically.

The Reduction-In-Void Model is set up combining various relationships and formulas to simulate the reduction in void case. For this model, an assumption is made that the mass inside the dunnage bag remains constant, disregarding the effect of material stress relaxation, creep and air permeation. In order to simulate this motion of a bag being constrained between two plates, the model decreases the void size from 305 mm iteratively down to 180 mm. The void size refers the height between the two plates. A vital concept for this model is that the void size is assumed to be the same as the diameter of the dunnage bag when viewed from the side. Figure 6.3 shows a 3D model of the actual dunnage bag created using a 3D scanner along with other shapes to explain the concept of void size.

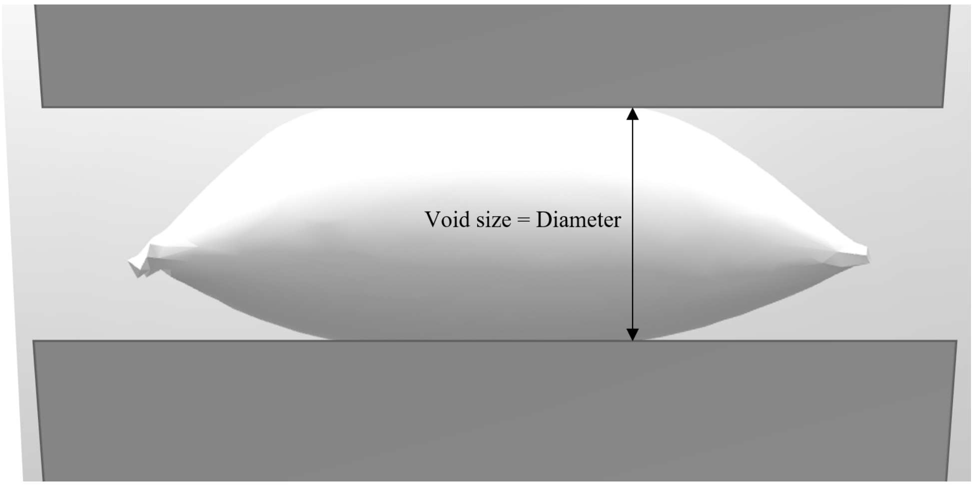
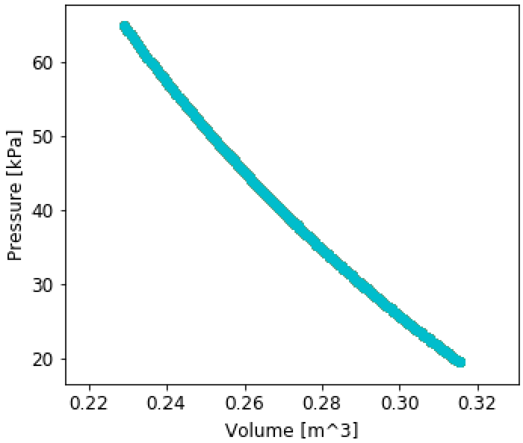


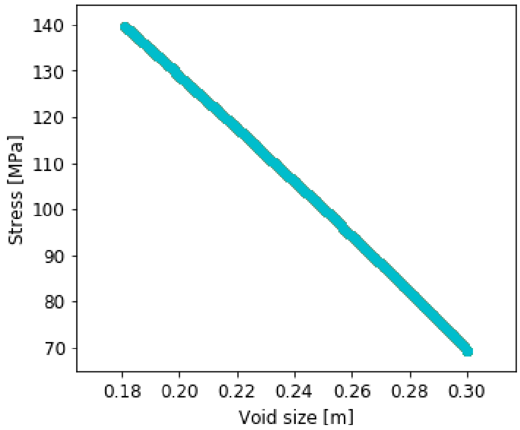
Figure 6.3: The void size between the plates are assumed to be the diameter of the dunnage bag.

The volume inside the dunnage bag is determined using the geometric formula explained in Section 6.1.1. Since the void size (which is the "diameter" of the dunnage bag) decreases for this model, the volume changes. Then the pressure inside the bag is calculated by using the Ideal Gas Law, assuming that the mass of air inside the dunnage bag remains constant. From there, the stress of the bag can be determined by using Barlow's Formula. Once the stress has been calculated, the strain in both the weft and warp direction are calculated. The strain is calculated using the HK constitutive model. With the change in strain, both the length and width of the bag are updated accordingly. Then the diameter size is changed and the entire model is run again. Figure 6.5 on page 55 presents a flow diagram of how the Reduction-In-Void Model works. For iteration convergence, the first few values are disregarded. The names and descriptions of the functions can be found in Appendix D, while the coding can be found in Appendix E.

The material parameters, generated by the constitutive HK model, are used as the input values to the Reduction-In-Void Model. A comparison between the various critical parameters illustrates how the model simulates the reduction in void load case. Figure 6.4 a.) presents a graph comparing the pressure versus volume, while Figure 6.4 b.) shows a graph comparing the stress inside the dunnage bag versus the void size.



(a) Pressure [kPa] versus Volume [m^3]



(b) Stress [MPa] versus Void size[m]

Figure 6.4: Reduction-in-Void Model graphs

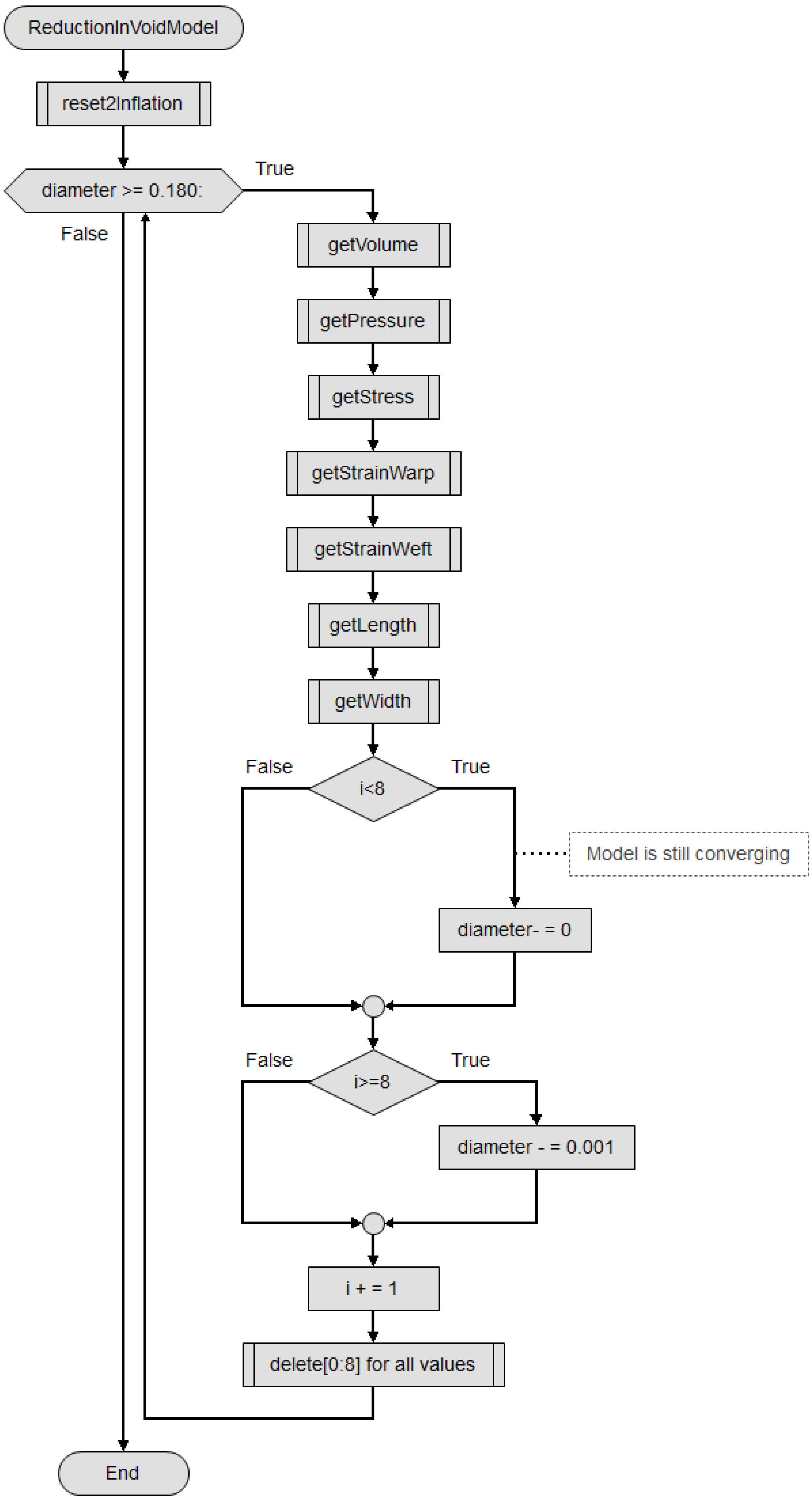


Figure 6.5: A flow diagram of the Reduction-In-Void Model algorithm

The reduction in void size load case iterates from 305 mm to 180 mm, this can be observed in Figure 6.6. Furthermore, the starting pressure of 20 kPa increases up to about 65 kPa in a single compression.

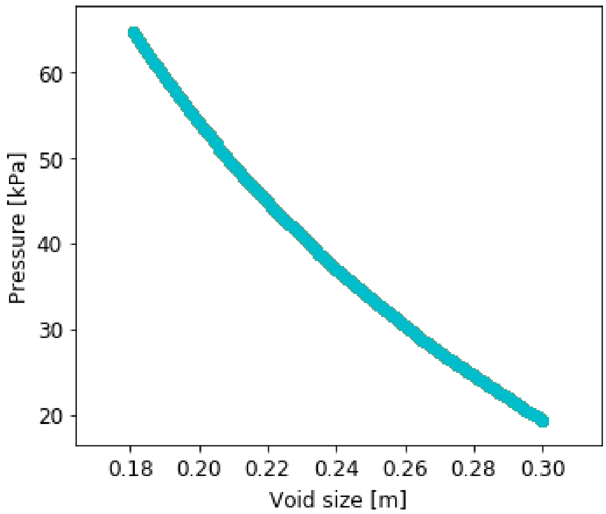


Figure 6.6: Pressure [kPa] versus Void size[m]

Figure 6.7 shows a comparison between the model results and the experimental results. It can be observed that the load case displayed slightly higher pressure than the model. This can be due to the volume approximation and the material stiffness calculation. The volume and material stiffness are confounding variables, since both influences the results simultaneously. With reference to the effect of the material stiffness calculation, Barlow's equation creates a relation between the pressure and the stress, if the stress was calculated to be higher (for the same void size), the pressure at compression would be higher, resulting in a smaller deviation between the model and the experimental values. Then, with reference to the volume approximation, the pressure in the Reduction in Void model is calculated using the Ideal Gas Law, thus if the volume calculation approximates the volume a bit too large, the pressure will be lower than that of the experimental results, as seen in Figure 6.7. Lastly, an underestimation of the mass of air inside the bag would also result in a lower pressure.

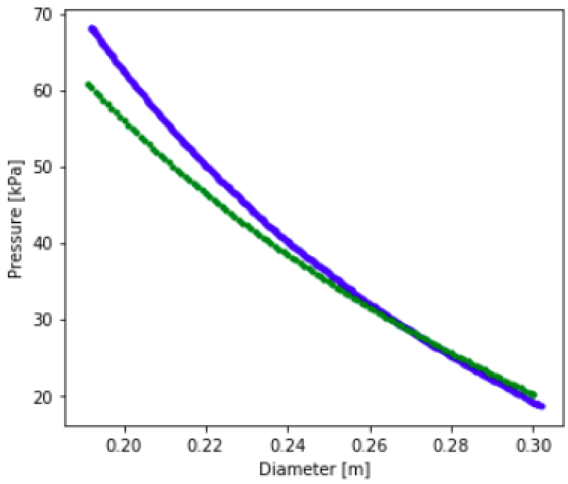


Figure 6.7: Comparison between the Reduction In Void model results (green line) versus the load case experiment (blue line).

6.3 Permeability Model

The Permeability Model accounts for the air that permeates through the interior polyethylene layer. Since the Reduction-In-Void Model assumes that the air inside the bag remains constant for that load case, it should be accounted for. Similar to a balloon, the dunnage bag will not maintain the air continually. Therefore, the Permeability Model calculates the mass loss rate of the air based on the permeability characteristics determined by the permeability experiment explained in Chapter 3. Polyethylene displays viscoelastic behaviour which means that it is rate- and temperature-dependent. From the experimental results in Chapter 4, it can be observed that the permeability of a material changes as temperature changes. However, for this model, the temperature is fixed at 30^{o}C since the load case experiments where performed at this temperature. Furthermore, the effects of creep and stress relaxation of the polypropylene threads are disregarded for this model.

The Permeability Model starts by calling the "reset2Inflation", which resets all the initial values to that of a constrained inflated bag. Then the mass loss rate is determined by using the formula in Equation (6.3.1). The new mass within the bag can be calculated by using the mass loss rate formula, as shown in Equation (6.3.2). The pass reduces as the time increments. Figure 6.8 shows the flow diagram of the Permeability Model.

$$\dot{m} = \frac{\varphi \times \Delta P \times A}{thickness} \tag{6.3.1}$$

$$\dot{m} = \frac{m_2 - m_1}{time} \tag{6.3.2}$$

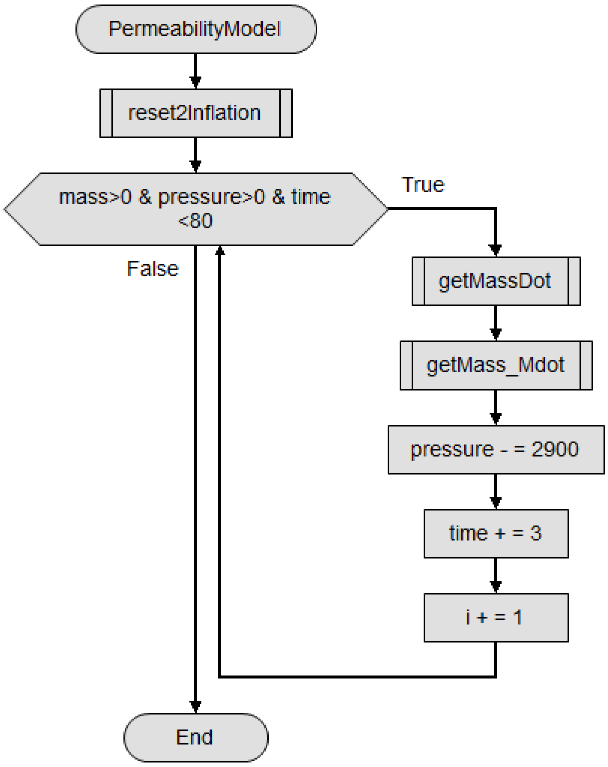


Figure 6.8: A flow diagram of the Permeability Model algorithm

Figure 6.9 presents the results of the Permeability Model, whereby the mass within the bag permeates, while Figure 6.10 shows the results for pressure and mass over time.

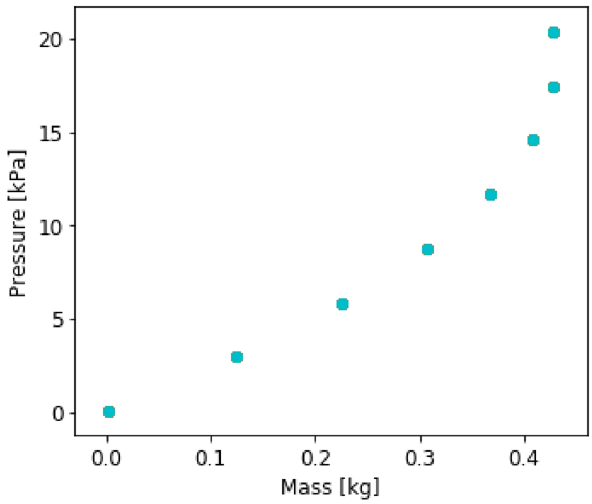
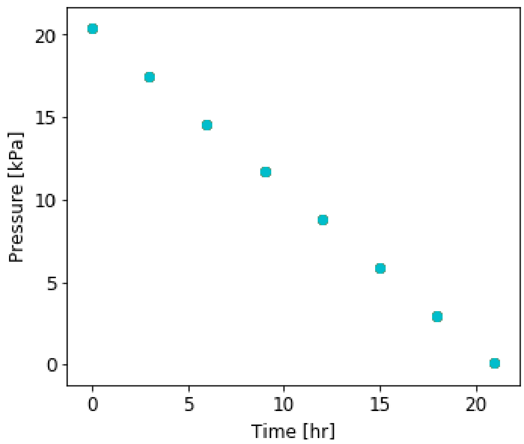
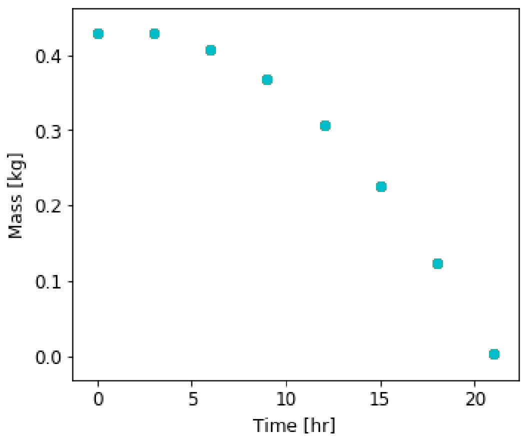


Figure 6.9: Permeability Model results illustrating mass [kg] versus pressure [kPa].



(a) Pressure [kPa] versus Time [hrs]

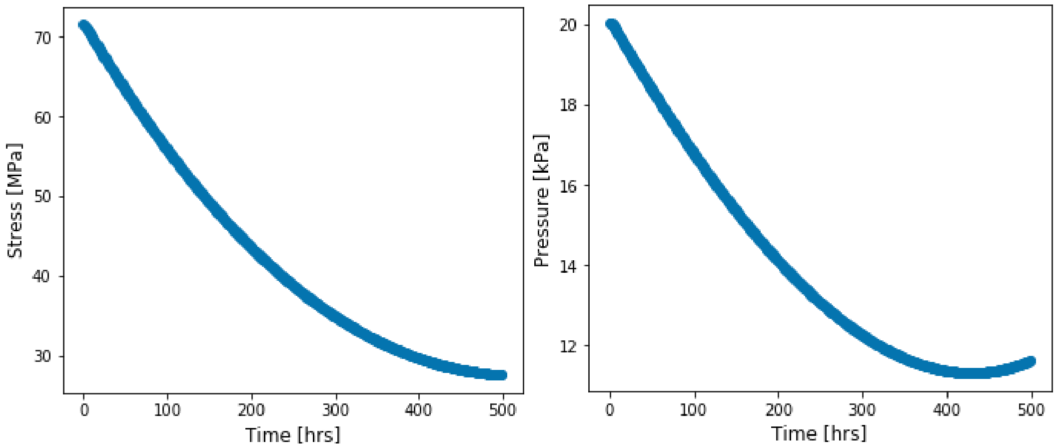


(b) Mass [kg] versus Time [hrs]

Figure 6.10: Permeability Model graphs

6.4 Stress Relaxation Model

Since the effect of stress relaxation and creep were disregarded in the Permeability Model, it has to be accounted for in this model. In reality, the dunnage bag experiences both theses phenomena at once. The polypropylene threads relax over time. For the Stress Relaxation Model, it is assumes that the stress decreases over time, while the strain remains constant and the effects of permeability are ignored. For a creep case, the strain decreases over time while the stress remains constant. However, this model only investigates the stress relaxation case. Figure 6.11 displays the results of the Stress Relaxation Model.



(a) Stress [MPa] versus Time [hrs] (b) Pressure [kPa] versus Time [hrs]

Figure 6.11: Results of the Stress Relaxation Model

The algorithm is as follows, the parameters are reset to inflation, using the "reset2Inflation" function. Then the pressure is calculated using the Ideal Gas Law formula and the volume is calculated using the volume approximation. Then, the stress is calculated using Barlow's formula. The dimensions of the bag and time are change each for iteration. Figure 6.12 displays the flow diagram of the Stress Relaxation Model.

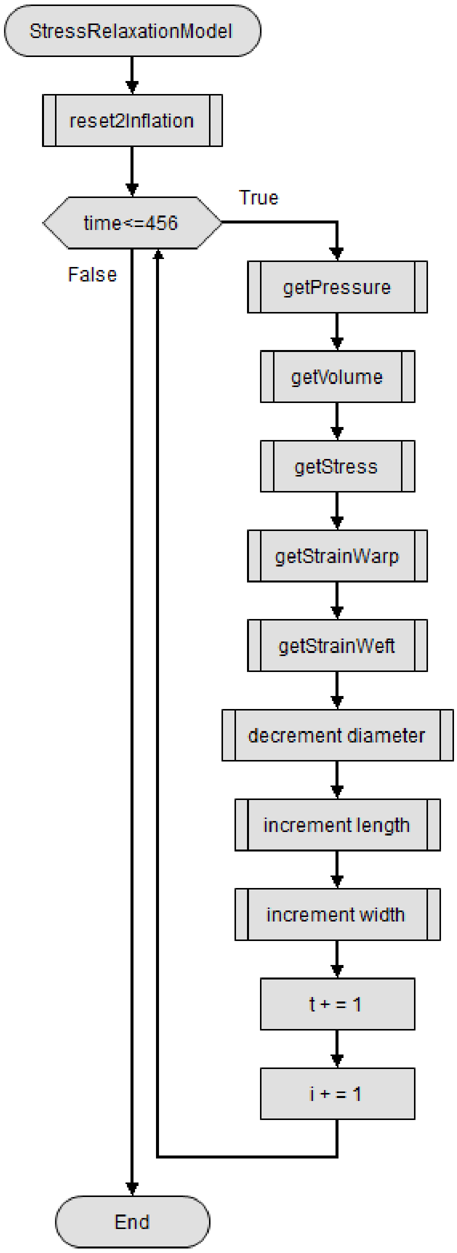
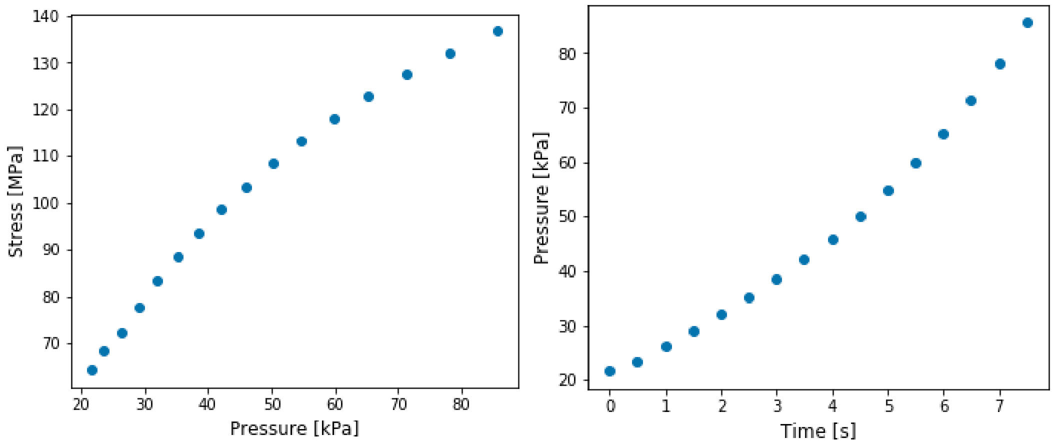


Figure 6.12: A flow diagram of the Stress Relaxation Model algorithm

6.5 Burst Model

During a typical trip, the truck may stop suddenly and then the dunnage bag will experience extreme compression forces from the boxes pushing against it. Thus the maximum pressure that a dunnage bag can withstand during compression plays a vital role in its success. Accordingly, the Burst Model simulates this load case. The model starts at the constrained inflation position of 20 kPa in a void size of 0.3 m, so the model calls the "reset2Inflation" function. From there, the volume is calculated using the volume approximation, then the pressure is calculated using the Ideal Gas Law. Next, the stress is calculated using Barlow's formula. The stress is then used to update the strain in both warp and weft directions, and the resulting length and width are also calculated. The void size is decremented and time are then incremented. Figure 6.14 on page 68 presents the flow diagram of the Burst Model.

The results of the Burst Model are displayed in Figure 6.13 a.) shows how the stress increases as the pressure increases, while Figure 6.13 b.) displays how the pressure increases over time.



(a) Stress [MPa] versus Pressure [kPa] (b) Pressure [kPa] versus Time [s]

Figure 6.13: Burst Model graphs

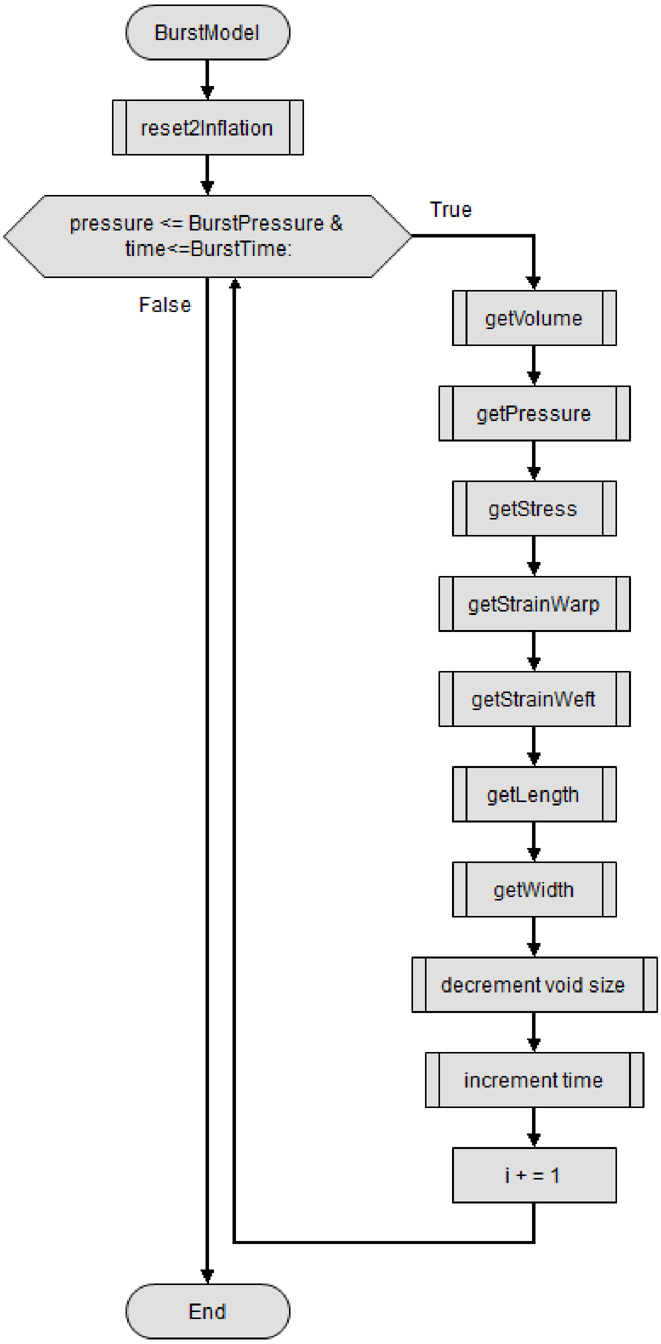
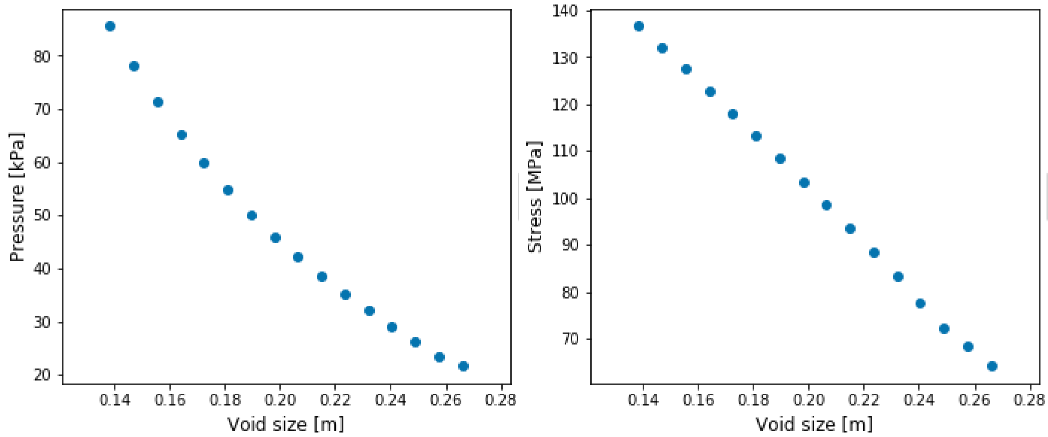


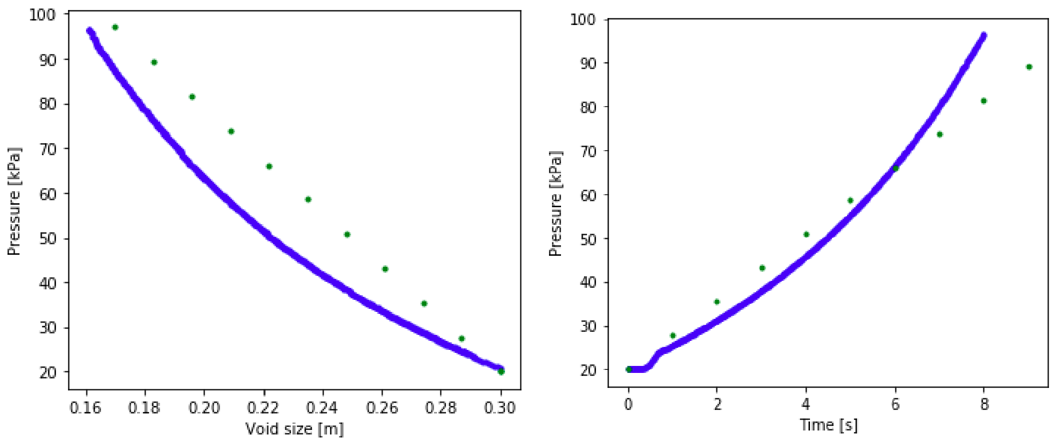
Figure 6.14: A flow diagram of the Burst Model algorithm

Figure 6.15 a.) displays the how the pressure increases, with decreasing void size and Figure 6.15 b.) shows the pressure increase over time. Figure 6.16 presents a comparison between the crush burst data (the blue line) versus the Burst Model (green dots). It can be observed that experimental plot tends to a quadratic curve whereas the model plot has been defined to a linear plot. This is due to fact that the pressure parameter is decremented and the diameter parameter is incremented.



(a) Pressure [kPa] versus Void size [m]   (b) Stress [MPa] versus Void size [m]

Figure 6.15: Burst Model graphs



(a) Void size [m] versus Pressure [kPa]   (b) Pressure [kPa] versus Time [s]

Figure 6.16: A comparison graph between the crush burst experimental data (blue line) and the Burst Model (green dots)

Chapter 7

Material Criterion

The Material Criterion is the final objective of this project. Now that the mathematical models have been established, based on the experimental results and the load cases, the material criterion can be developed. The intention with the material criterion is to create boundaries within which candidate materials can be discovered. By making use of the parametric models developed in Chapter 6, a range of candidate material properties can substitute the original dunnage bag material properties. Then, by either using stipulated standard AAR conditions or critical parameters from the mathematical models as criteria, the material properties can be filtered. A random selection of material properties within specified ranges will enhance the credibility of the material criterion. Accordingly, a Monte Carlo Analysis will be used. Finally, the correlation between material properties will be determined to be portray the best suited candidate material properties.

7.1 Material Criterion Algorithm

A Monte Carlo Simulation provides a method of testing various combinations of candidate material properties. Chapter 2.6 presents background to a Monte Carlo Simulation. A Monte Carlo Simulation is used so that it is possible to perform numerous iterations and test various material properties. The candidate material properties are generated by calling the different mathematical models (developed in Chapter 6), and selecting values from a distribution that has been pre-defined to run the various mathematical models. This means that random values of the tensile properties and permeation properties (within standard deviation limits) are generated. These various material properties are then fed into the mathematical models. Then the pass criterion for material properties are set up such that the candidate properties are able to generate model behaviour similar to the original double-layer dunnage bags. Thus the material property selection can be narrowed down for future candidate materials.

The algorithm for the material criterion was designed such that a user can define which model to run as well as the preferred output results. The model options refer to the mathematical models developed in Chapter 6. The algorithm for the material criterion can be described as follows:

- The user defines which model to run (1. Reduction-In-Void Model, 2. Permeability Model, 3. Stress Relaxation Model or 4. Burst Model).
- Then the user defines the type of output required. Type 1 runs 40 iterations and generates the model graphs with various material properties. Type 2 runs 10 000 iterations and generates the pass/fail results along 2D correlation histograms.
- Once the user has defined the two options, the Main function calls the MonteCarloSimulation() function and sends the number of iterations that are to be performed along with which model to run.
- Then the MonteCarloSimulation() function calls the user-specified model by using the specific "call" function (For example: CallReductionInVoid). It is from within the MonteCarloSimulation function where the iterations run.
- The "call" function then calls the specific model (For example:ReductionInVoidModel), as discussed in Chapter 6.
- Once all the iterations are done, the output is displayed.

Figure 7.1 displays a section of the flow diagram for the Main function of the Monte Carlo Simulation developed for the material criterion. The other two mathematical models (StressRelaxationModel and BurstModel) work in a similar manner. It can be observed in Figure 7.1 that the MonteCarloSimulation function calls all the models, thus Figure 7.2 displays the flow diagram for the Monte Carlo Simulation developed for the material criterion.

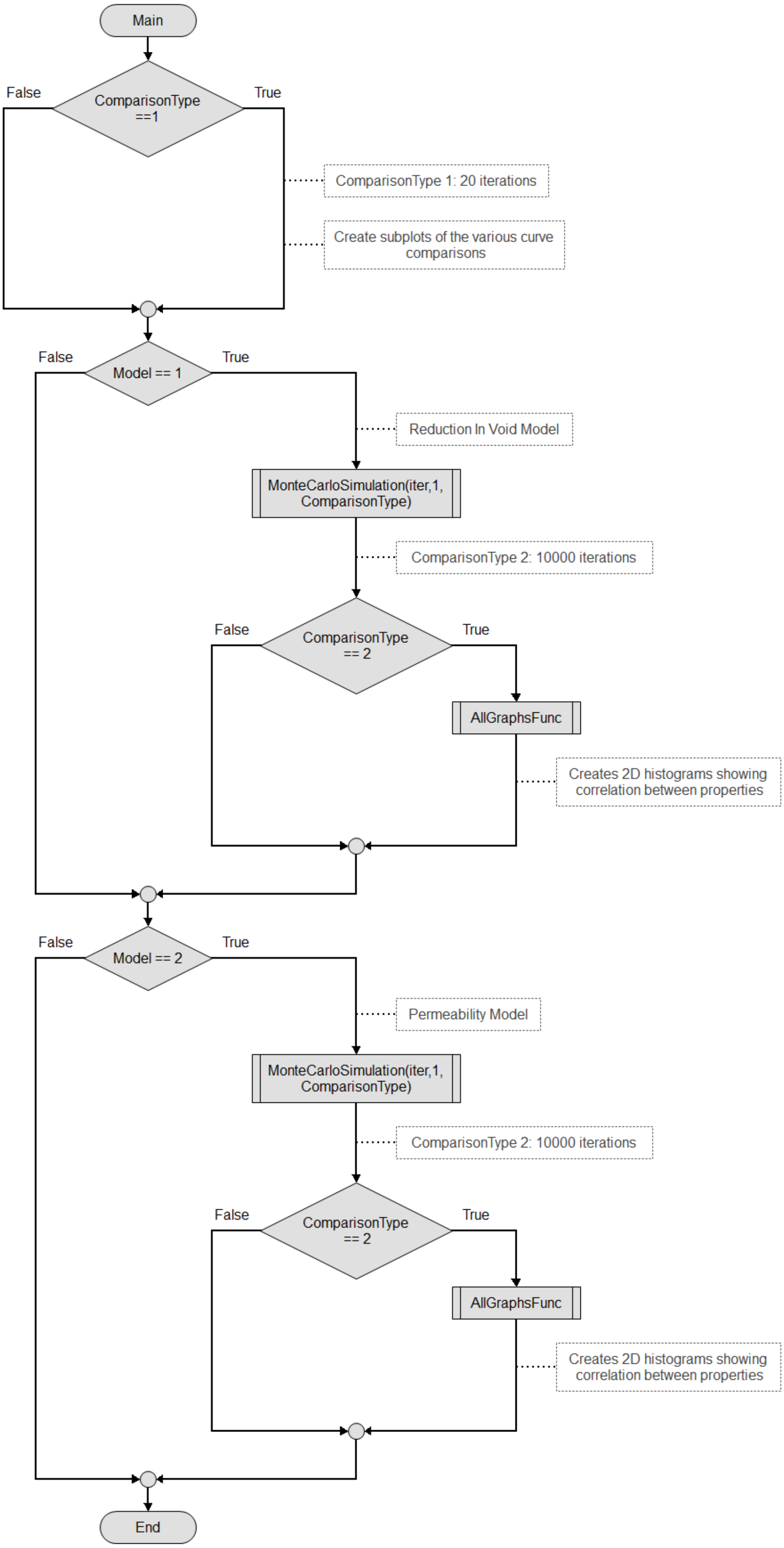


Figure 7.1: A section flow diagram of the Main function of the material criterion.

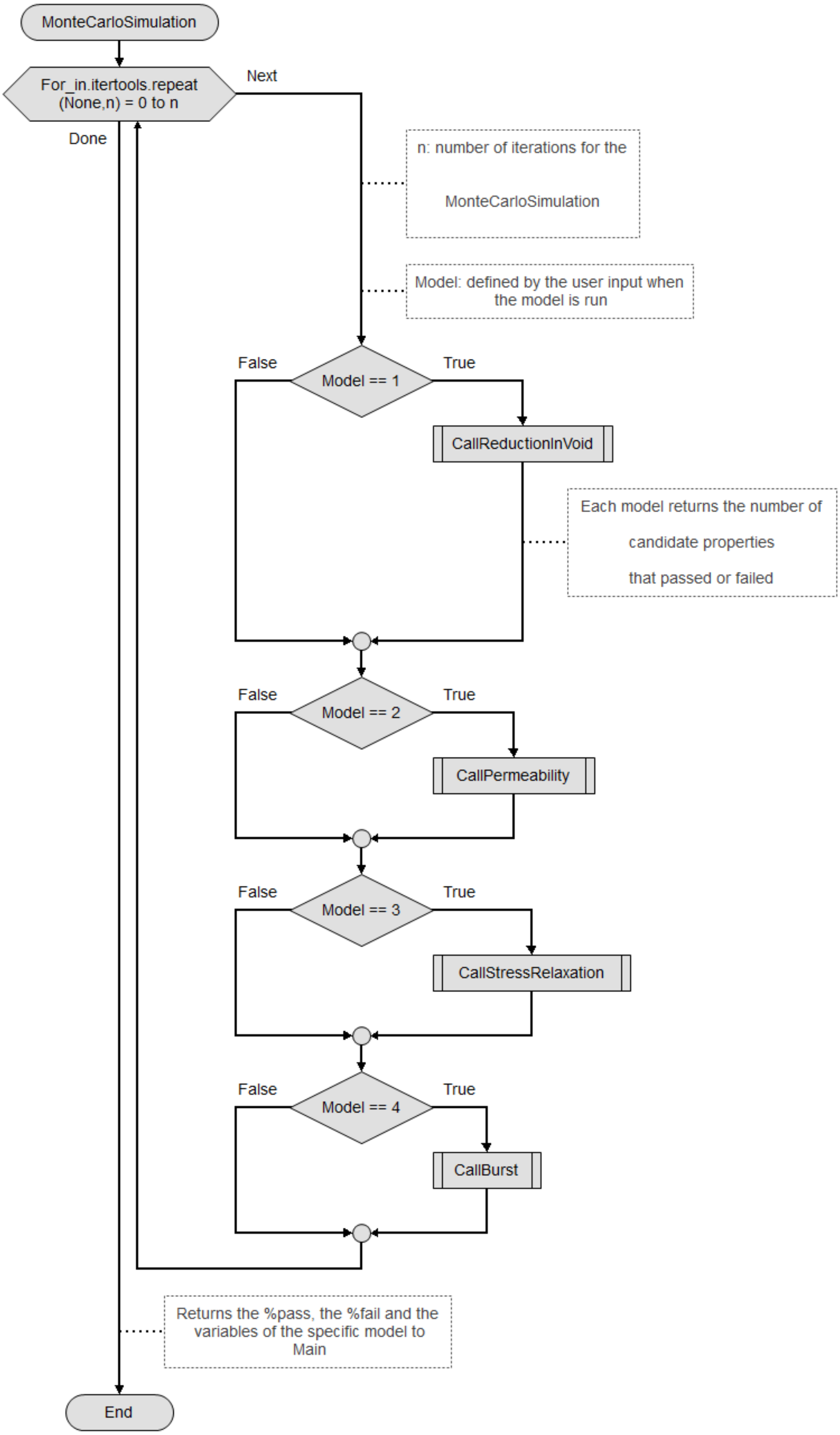
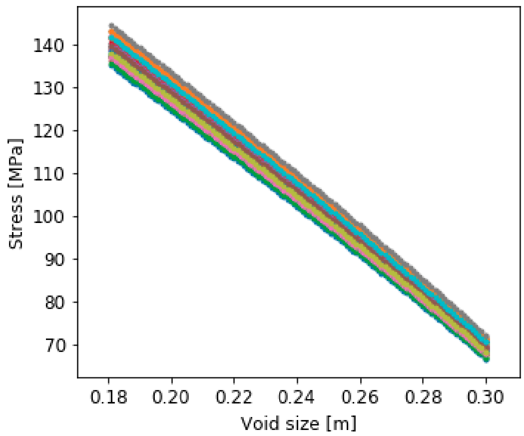


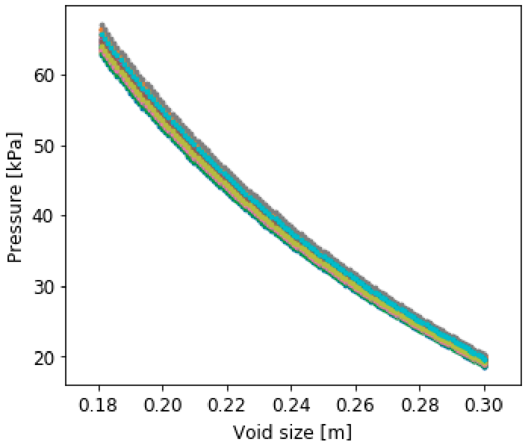
Figure 7.2: A flow diagram of the MonteCarloSimulation function algorithm

7.2 Monte Carlo Simulation Results

The material criterion was created such the different load cases could be evaluated separately. This creates a clear view of how the material properties affect each load case. For some of the load cases, the material property range is much wider than for other load cases. This can be observed in the comparison graphs presented below. To generate the comparison graphs, 40 iterations were run. This means that 40 different material property sets are tested. The "sets" refer to the combination of specific tensile moduli (E_1 and E_2), permeability, temperature and burst pressure. Each colour line or dot represents a different material property set. With the goal of ensuring that the same property set is compared throughout all the models, a random "seed" value was defined. This ensures that the same pattern of randomness is applied each time the model is run. Figure 7.3 and Figure 7.4 shows the comparison graphs of the Reduction In Void Model. Each line on the graph represents a different material property set (E_1 and E_2). The resulting pressure and stress deviates from the original Reduction In Void Model discussed in Chapter 6.2. In Figure 7.4, it can be observed that the different material property sets influence the strain values and the gradient values.

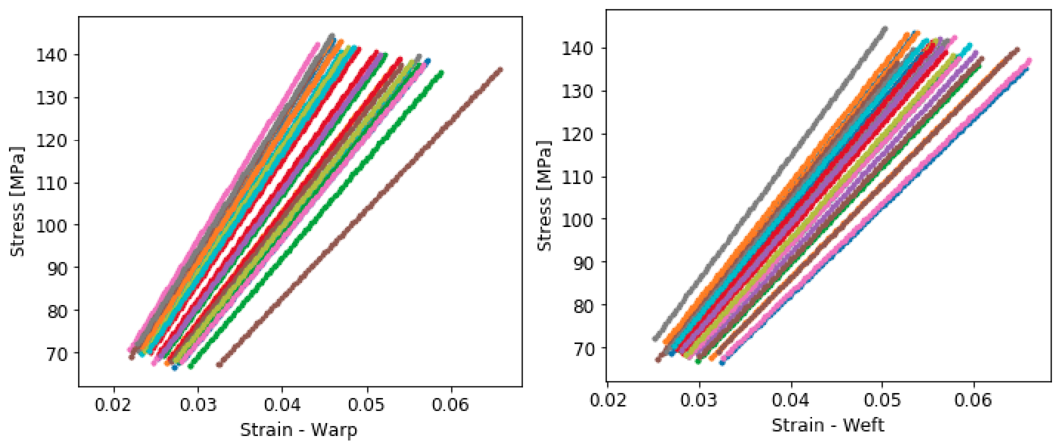


(a) Stress [MPa] versus Void size [m]



(b) Pressure [kPa] versus Void size[m]

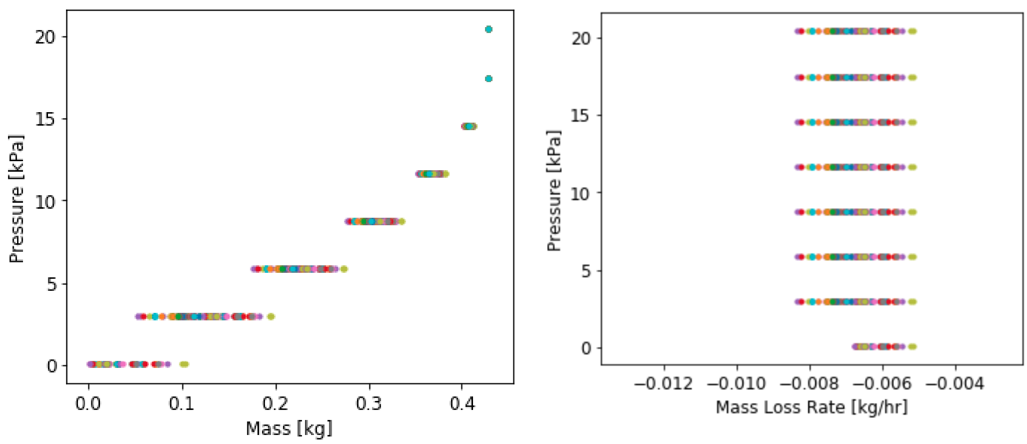
Figure 7.3: Reduction in Void Model candidate material properties graphs



(a) Stress [MPa] versus Warp Strain (b) Stress [MPa] versus Weft Strain

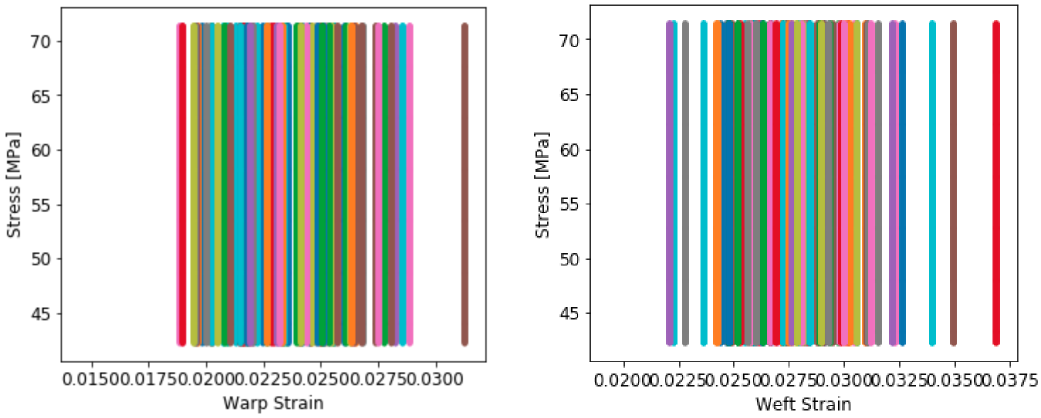
Figure 7.4: Reduction in Void Model candidate material properties graphs

The Permeability Model comparison graphs can be viewed in Figure 7.5. The mass and pressure for all material property sets start at the same values. However, in Figure 7.5 a.) it can be seen that as the mass and pressure loop to zero, the value diverges. This indicates that the material property set, specifically the permeability, influences how much mass and pressure is lost. Figure 7.5 b.) shows how different permeability values influences the mass loss rate. The Stress Relaxation Model comparison graphs can be seen in Figure 7.6, whereby it can be observed that strain of the polypropylene material differs in the weft direction to that of the warp direction.



(a) Pressure [kPa] versus Mass [kg] of air in the dunnage bag (b) Pressure [kPa] versus Mass Loss Rate [kg/hr]

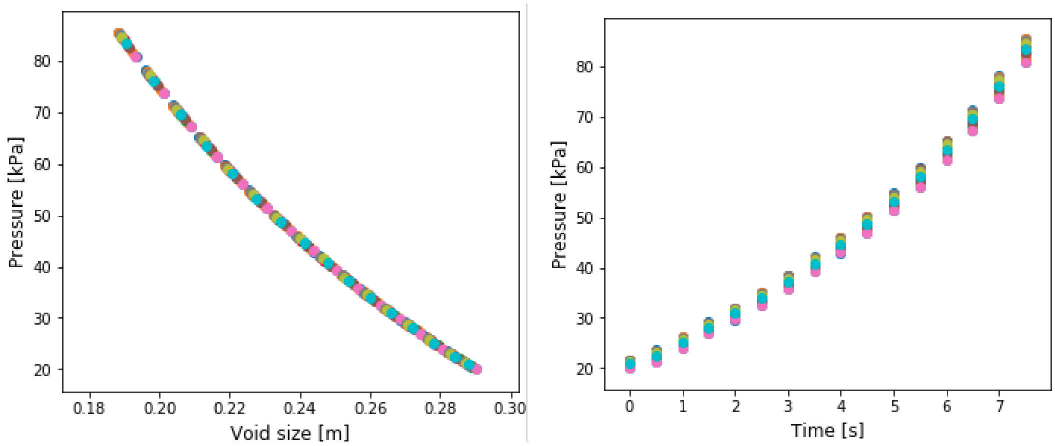
Figure 7.5: Reduction in Void Model candidate material properties graphs



(a) Stress [MPa] versus Warp Strain (b) Stress [MPa] versus Weft Strain

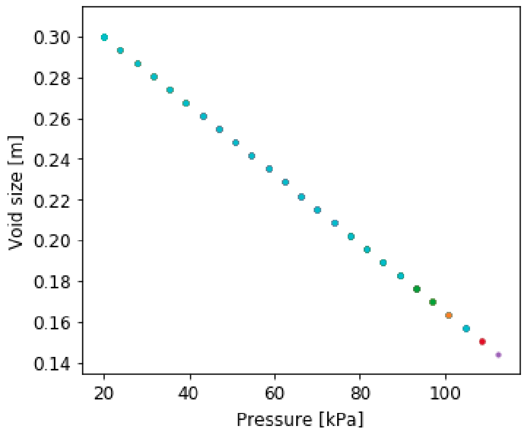
Figure 7.6: Stress Relaxation Model candidate material properties graphs

The Burst Model was set up such that the effect of the tensile moduli can be observed in the final burst pressure. It can be seen in the comparison graphs presented below that the final dots display different colours. This indicates the difference in burst pressures and times. The comparison graphs can be viewed in Figure 7.7 and Figure 7.8.

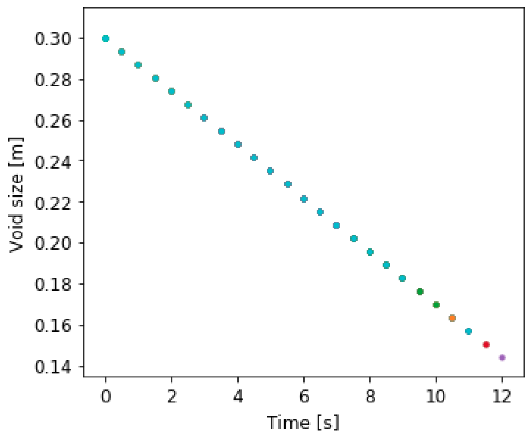


(a) Pressure [kPa] versus Volume [m^3] (b) Pressure [kPa] versus Time [hr]

Figure 7.7: Burst Model candidate material properties graphs



(a) Void size [m] versus Pressure [kPa]



(b) Void size [m] versus Time [s]

Figure 7.8: Burst Model candidate material properties graphs

7.3 Material Properties Analyses

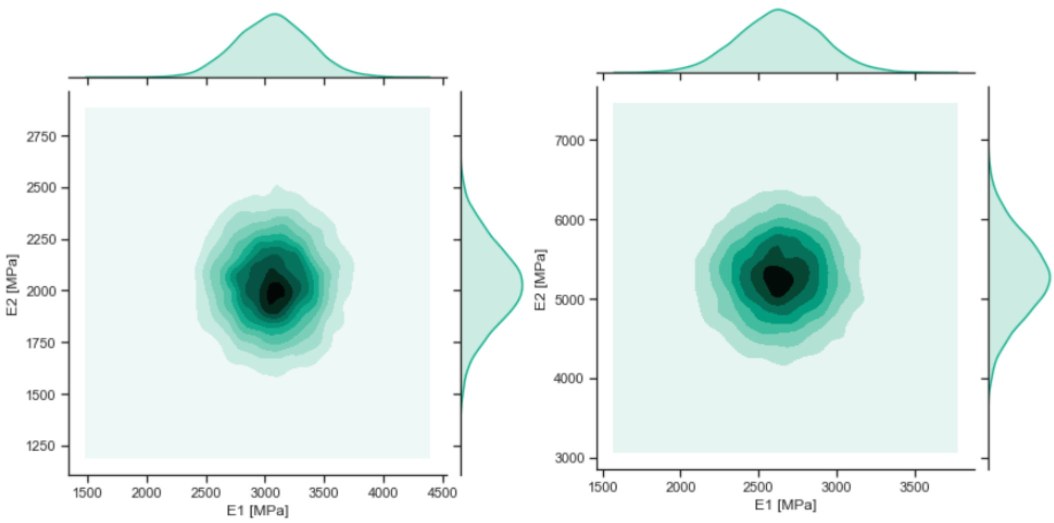
In Chapter 7.2 the results of the various material properties within the different mathematical models were discussed. In this section the criteria for each model is discussed along with the results of the property sets that failed or passed the criteria. Table 7.1 presents an explanation of the criteria set up for each model. The flow diagrams of each model along with the exact criteria can be viewed in Appendix D. From the criteria for the various models, all the material properties were evaluated and filtered. The results of the material criterion of the Reduction In Void Model is displayed in Figure 7.9. Furthermore, the filtered material property sets were then used to generate 2D correlation histograms. Figure 7.10 indicates that the normal distribution used to generate the random value of tensile moduli were accurate. These material property sets were run with the Reduction In Void Model. A correlation between E_1 and E_2 values for both warp and weft direction of the Reduction in Void Model can be observed. Figure 7.11 and Figure 7.12 show the 2D histograms for the passed and failed values. The 2.7% pass rate can be seen in the contrast of dot density. The darker the shade of the dot is, the better correlation the material properties have.

Table 7.1: Criteria used for each mathematical model

Model	**Criteria**
Reduction In Void Model	The criteria for the reduction in void model is based on the ratio of the critical parameters just after inflation to the parameters just after compression. These critical parameters are stress and strain in both warp and weft directions.
Permeability Model	The material properties pass the Permeability Model Criteria when the mass loss rate of the candidate materials are smaller than or equal to that of the original mass loss rate determined by the original material properties.
Stress Relaxation Model	According to the AAR regulations, a dunnage bag should maintain 60% of the original pressure of 19 days, thus a material property passes the criteria if it results in a pressure greater than or equal to 12 kPa.
Burst Model	In the large scale experiment where the dunnage bag was crushed between plates up until burst, it was determined that the burst pressure was approximately 96 kPa at a time of 8 s. Accordingly, the candidate material that burst at a higher or similar pressure in the same time or longer, pass the criteria.

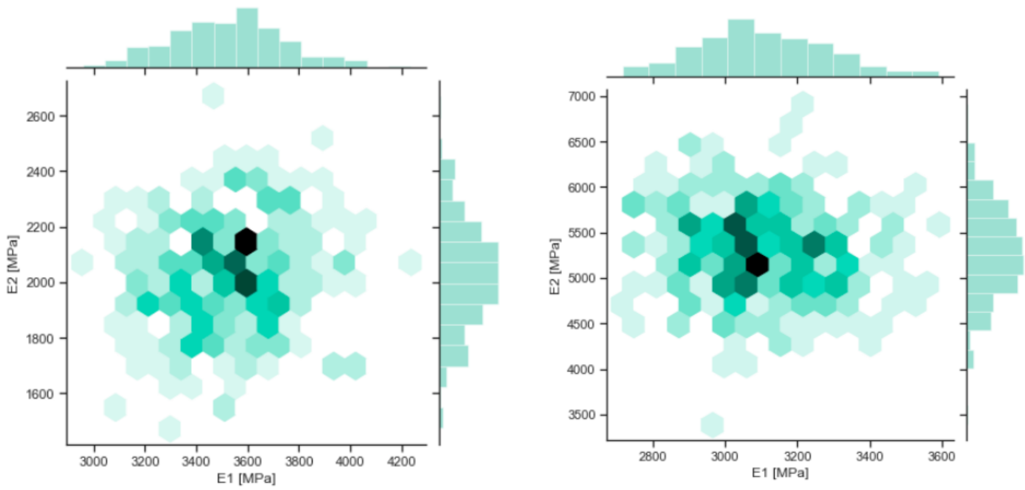
```
Reduction In Void Model
Candidate material property pass rate =  2.7 %
Material property failure rate =  97.3 %

Number passed : 270
Number failed: 9730
```

Figure 7.9: The results of the material criterion of the Reduction In Void Model



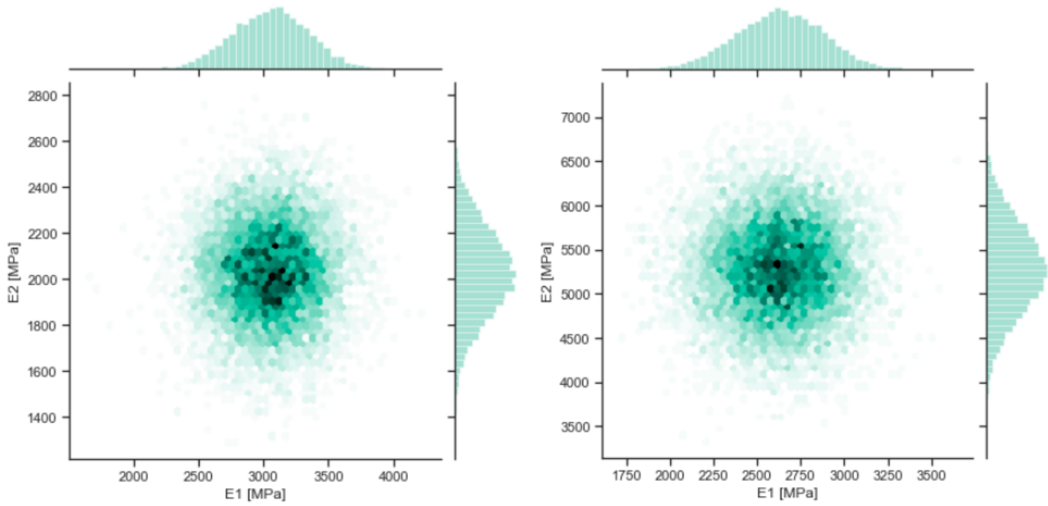
(a) All warp tensile moduli (b) All weft tensile moduli

Figure 7.10: Correlation between E1 and E2 for all material property sets in the Reduction In Void Model



(a) Warp tensile moduli that passed (b) Weft tensile moduli that passed

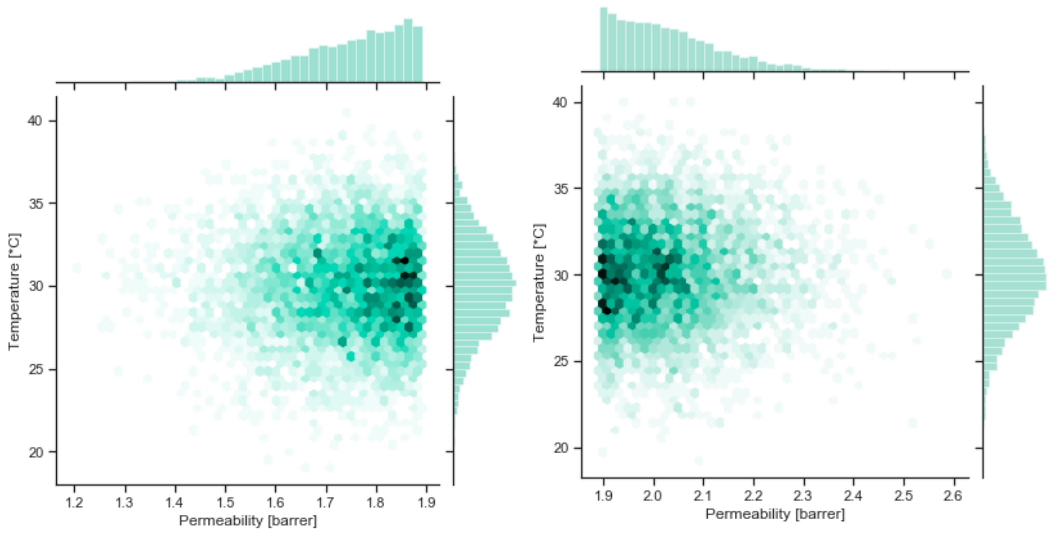
Figure 7.11: Correlation between E1 and E2 for the passed material property sets in the Reduction In Void Model



(a) Warp tensile moduli that failed (b) Weft tensile moduli that failed

Figure 7.12: Correlation between E1 and E2 for the failed material property sets in the Reduction In Void Model

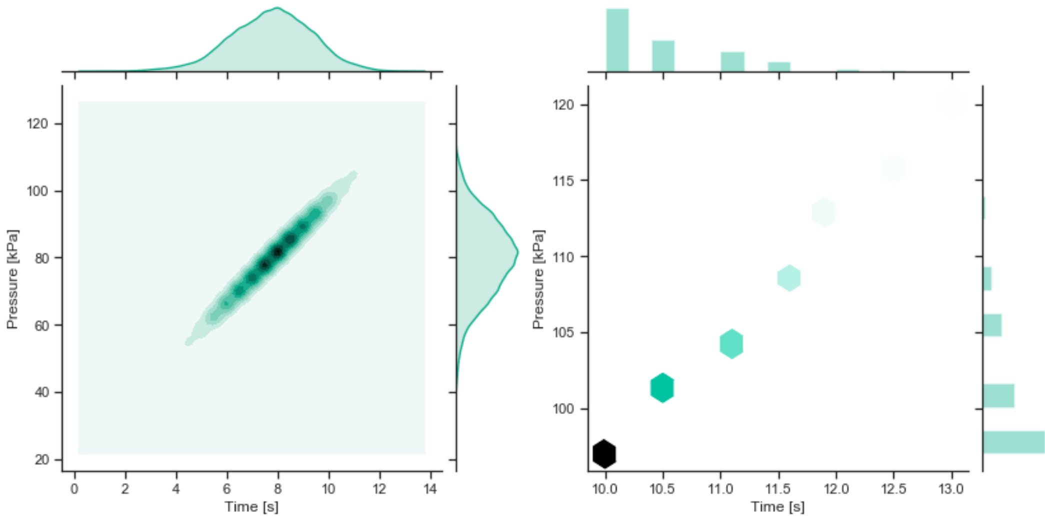
With the different permeability and temperature sets sent to the Permeability Model, 52.83% of the material property sets passed the criteria. Permeability values equal to or smaller than the original tested permeability value passed the material criterion. Figure 7.13 shows the correlation graphs for the passed and failed sets within the Permeability Model.



(a) Passed material properties (b) Failed material properties

Figure 7.13: Correlation between temperature and permeability for the material property sets in the Permeability Model

The Burst Model provided interesting results, Figure 7.14 shows the 2D correlation histograms of all the critical parameters and the passed critical parameters. It can be seen that very few material property sets passed the criteria, with a 9.48% passing rate. The exact values of the material property sets can be found in Appendix C.



(a) All critical parameters (b) Passed critical parameter

Figure 7.14: Correlation between pressure and time for the material property sets in the Burst Model

Chapter 8

Conclusion

The main of objective of this project was to create a material criterion of the current double-layered dunnage bag. The material criterion was developed with the intention to create reasonable bounds for candidate material properties within which candidate materials can be discovered. This was done by firstly setting up a detailed plan of how all the interdisciplinary fields connect and consequently how the experimental data could be tied into a material criterion model. Then, the different load cases of the current double-layered dunnage bags were tested by performing large-scale tests, namely, inflation, cyclic behaviour and bursting. The data from the large-scale tests were also used to develop criteria for the material criterion.

The next phase was to perform small-scale experiments. Various uniaxial tensile tests were performed on the polypropylene threads in both the weft and warp direction. The experimental data was analysed by making use of the train-test-split method to ensure unbiased modelling conditions. From there, different constitutive modelling techniques were investigated and applied. It was found that the HK constitutive model best describes the data from the tensile tests. The second small-scale experiment that was conducted was permeability. The permeability of the polyethylene material was tested at different temperatures. The data from the permeability experiments were compared to literature to validate it and the permeability data was modelled by a polynomial fit.

From here the model creation phase started, whereby the volume of the dunnage bag was estimated. This was done by referring to literature and testing various shape-combined volume formulas. The next step was to find a way of connecting the large-scale tests to the small-scale tests. This was done by making a few assumptions on how the bag functions. The dunnage bag was assumed to be a thin-walled pressure vessel, which enabled the use of Barlow's formula. Barlow's formula relates the stress in the bag to pressure and the diameter. The next assumption that was made is that the void size between the plates are same as the diameter of the bag. This assumption connected the volume formula to Barlow's formula. Box (1976) makes a valid statement: "Since all models are wrong the scientist must be alert to what is importantly wrong". The use of Barlow's formula is somewhat ambitious but necessary to connect all the loose ends. Box (1976) makes another statement: "It is inappropriate to be concerned about mice when there are tigers abroad". At this stage there were three unknowns (stress, pressure and volume) and only two equations. So, it was assumed that the air inside the dunnage bag behaves like an ideal gas. This enabled the use of the Ideal Gas Law. Lastly, the HK constitutive model was added, to account for the stress-strain relationship and consequently length and width could be calculated. These equations created a closed-loop within which most of the models could be calculated.

Four different mathematical models were created, namely, the Reduction-In-Void Model, the Permeability Model, the Stress Relaxation Model and the Burst Model. The mathematical models of each load case were developed using the equations described. The models were validated by comparing the output graphs to that of the large-scale experiments. From here it was possible to replace the original material properties with candidate material properties. This was done by using a Monte Carlo simulation that generated random values from a normal distribution and iterated through all the models. The output were comparison graphs that display the effect of the different material properties on the critical model parameters (pressure, volume, mass, stress etc.). Lastly, criteria for each mathematical model was set up based on either AAR stipulations or the large-scale experimental results. Then the candidate material properties were evaluated and split into pass or fail material properties. These results were displayed using 2D correlation histograms that showed how the material properties correlated. This make it possible to discover candidate material since a search criteria, of which material properties will possibly display similar behaviour to that of the original double-layered dunnage bags, was created. The overall design of the project that involved configuring which experiments to perform, what load cases to investigate, what assumptions to make, which equations to use and how it all ties in together was the most challenging and time-consuming part of the project. However, without a detailed plan the material criterion could perhaps not be created.

Future work could include refining the model by investigating the effects of plastic strain, this could be included in the Stress Relaxation Model along with a component of creep. Furthermore, the effects of in-plane stress could be investigated by performing bi-axial tensile tests and incorporating the data into the model. Lastly, the Reduction-In-Void Model could be altered such that it performed cyclic behaviour. The material criterion has created a platform that has combined small-and-large scale parameters that can aid any model creations process in the future.

Appendices

Appendix A

Tensile Tests Thread Comparison

A comparison is drawn between the different thread-size samples. The results of the tensile tests have been normalised against the number of threads. This was done to visualise the correlation between the different tests. Figure A.1 presents the normalised data in the warp direction, where Figure A.2 presents the normalised data in the weft direction. It can be seen that the 6-, 7- and 8-thread samples display similar results, while the single thread sample withstands a slightly larger force. The gripping methods of the single- and multiple-thread samples differ, this may influence the results.

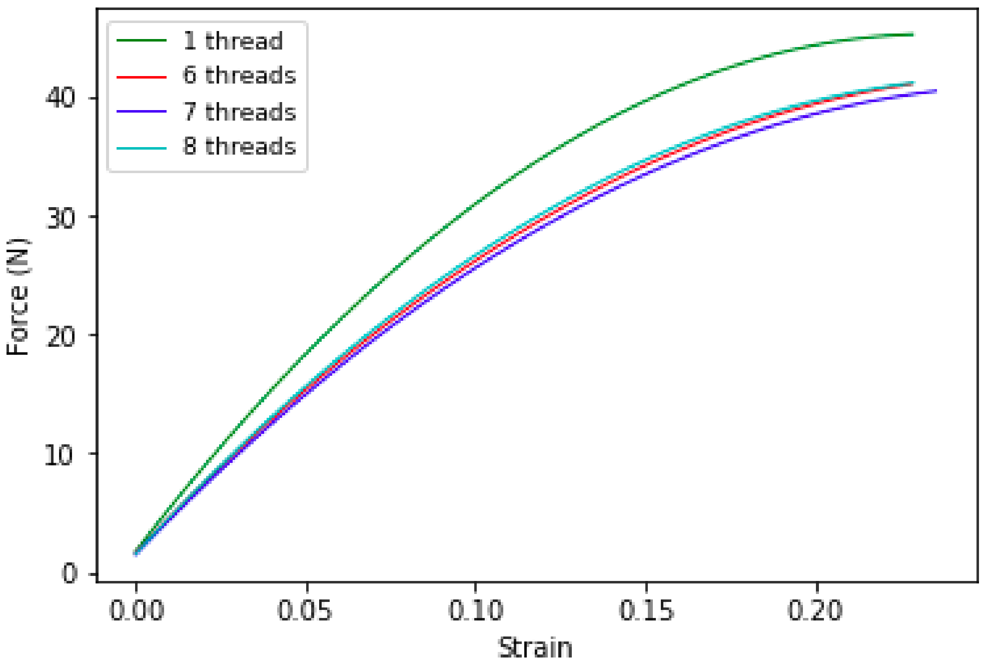


Figure A.1: Normalised tensile test thread comparison in the warp direction

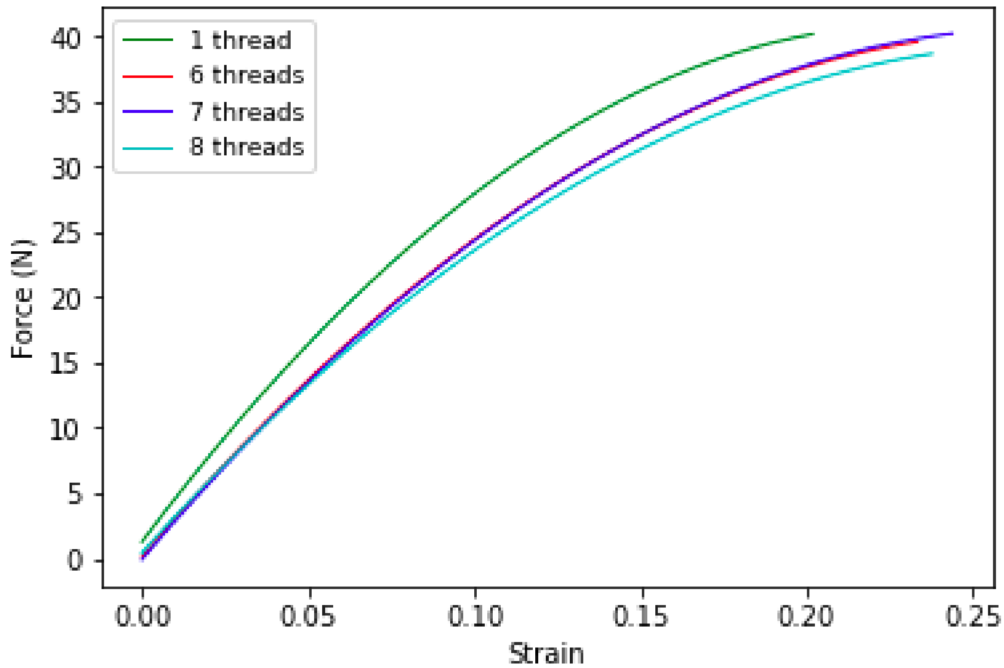


Figure A.2: Normalised tensile test thread comparison in the weft direction

Appendix B

Constitutive Model Derivation

In Section 2.4, the concept of constitutive modelling is discussed, along with how the models work. The H-K model, also known as the standard linear model, consists of a spring (E_1) coupled in series with the Maxwell model (E_2, η_2) (Roylance, 2001). Figure B.1 shows how the mechanics of the model work. The derivation of the HK model is illustrated in this section. The other constitutive models were also derived in a similar manner.

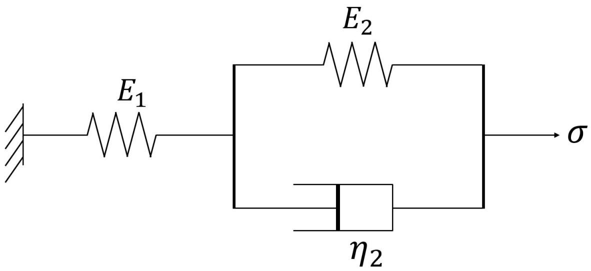


Figure B.1: H-K Model

$$\sigma = \sigma_1 = \sigma_2$$

$$\sigma = E_1\varepsilon_1 = E_2\varepsilon_2 + \eta\dot{\varepsilon_2}$$

$$\dot{\varepsilon} = \dot{\varepsilon_1} + \dot{\varepsilon_2}$$

$$\dot{\varepsilon} = \frac{\dot{\sigma}}{E_1} + \frac{\sigma}{\eta_2} - \frac{E_2\varepsilon_2}{\eta_2}$$

$$\varepsilon_2 = \varepsilon - \varepsilon_1$$

$$\varepsilon_2 = \varepsilon - \frac{\sigma}{E_1}$$

The differential equation has to be solved using an integration constant (K). The equation is solved for a state of constant stress. At $t = 0$, immediately after applying the stress, the strain will be entirely from the lone spring ($\varepsilon_1 = 0$), therefore:

$$\varepsilon(t = 0) = \frac{\sigma}{E_1}$$

$$\varepsilon = \frac{\sigma}{E_1} + \frac{\sigma}{\eta_2} - \frac{E_2}{\eta_2}\left(\varepsilon - \frac{\sigma}{E_1}\right)$$

$$\dot{\varepsilon} + \frac{E_2}{\eta_2}\varepsilon = \frac{\dot{\sigma}}{\eta_1} + \frac{\sigma}{\eta_2}\left(1 + \frac{E_2}{E_1}\right)$$

$$\frac{\sigma}{E_2} = K\frac{E_2 + E_1}{E_1E_2}\sigma$$

$$K = \frac{\sigma}{E_1}\left(1 - \frac{E_2 + E_1}{E_2}\right) = \frac{\sigma}{E_1}\left(1 - \frac{E_1}{E_2} - 1\right) = -\frac{\sigma}{E_2}$$

$$\varepsilon(t) = -\frac{\sigma}{E_2} exp\left(\frac{-E_2 t}{\eta_2}\right) + \frac{E_2 + E_1}{E_1 E_2}\sigma$$

$$\varepsilon(t) = \frac{\sigma}{E_2}\left(1 + \frac{E_2}{E_1} - exp\left(\frac{-E_2 t}{\eta_2}\right)\right)$$

Finally resulting in the equation described in Section 2.4:

$$\sigma = E_1\varepsilon\left(1 + \frac{E_1}{E_2}(1 - \exp(-\frac{E_2}{\eta_2}t))\right)$$

Appendix C

Material Criterion Candidate Results

Table C.1, Table C.2, Table C.3 and Table C.4 present the candidate material property sets that passed the criteria.

Table C.1: Reduction-In-Void Model: tensile moduli in the warp direction that passed.

	Warp: E1 [MPa]	Warp: E2 [MPa]
0	3607.685462	2112.263609
1	3639.427569	1832.507644
2	3656.412208	2331.683370
3	3303.388240	2198.245035
4	3404.127528	2294.619224
5	3331.518833	1867.547159
6	3018.855107	2244.061987
7	3282.632938	1727.220687
8	3964.969823	2076.254347
9	3653.740395	1692.637654
10	3171.715299	1985.614335
11	3665.250135	2282.822934
12	3737.887347	1986.356282
13	3109.045473	2275.645391
14	3382.392142	2051.720262
15	3612.440918	2024.782761
16	3717.139177	1861.954443
17	3543.048656	2052.782784
18	3862.970987	2113.109660
19	3740.798819	2121.641964
20	3478.181920	2009.628085
21	3572.478453	2247.319587
22	3482.426525	2157.995044
23	3599.317870	2134.299117
24	3398.665183	1634.560472
25	3529.824042	1702.108726
26	3232.865262	1889.701257
27	3516.122305	1994.487273
28	3200.387388	1850.669889
29	3607.510815	1756.595359

Table C.2: Reduction-In-Void Model: tensile moduli in the weft direction that passed.

	Weft: E1 [MPa]	Weft: E2 [MPa]
0	2898.005866	6464.954298
1	2890.443374	5201.501599
2	3132.623761	5759.962050
3	3210.672226	5987.319217
4	3351.362591	5242.397131
5	3259.086387	4605.858736
6	3476.680307	5381.523097
7	3306.526550	6216.213362
8	2897.293038	4459.154685
9	3069.032040	5169.770135
10	3290.148478	5383.811069
11	2887.406907	4743.128621
12	2877.412856	5752.208605
13	3400.258642	4967.795393
14	3312.266333	5051.209290
15	3055.949563	4852.163447
16	3019.219529	5894.413509
17	3044.930419	5183.759019
18	2800.228881	5358.845428
19	2883.586157	5774.547214
20	2997.797752	6345.129459
21	3064.385040	5356.973398
22	3081.927324	5128.174655
23	2947.182829	5658.070216
24	3284.049356	5272.310986
25	3003.174321	5581.381693
26	3210.919557	5565.503588
27	2967.961943	6185.923352
28	3290.432126	4971.653059
29	2953.283428	5541.031758

Table C.3: Permeability Model: permeation versus temperature material properties that passed.

	Permeability [barrer]	Temperature [*C]
0	1.559221	35.852326
1	1.576587	29.361779
2	1.874702	31.284996
3	1.753577	28.921341
4	1.573523	31.388347
5	1.821428	30.168496
6	1.804203	33.667335
7	1.881974	35.357611
8	1.641149	32.908190
9	1.829615	32.407369
10	1.798191	35.547791
11	1.753225	30.095492
12	1.867171	35.140028
13	1.685562	32.044784
14	1.813449	25.875146
15	1.672376	30.156495
16	1.872615	26.495720
17	1.876800	31.137455
18	1.792844	31.444444
19	1.767705	29.286235
20	1.662638	32.343594
21	1.760162	28.808185
22	1.582408	31.831138
23	1.515979	30.566336
24	1.749895	34.609131
25	1.854441	33.410674
26	1.634373	34.974392
27	1.629159	25.959847
28	1.668157	27.807967
29	1.868414	29.678084

Table C.4: Burst Model: critical parameters that passed.

	Pressure [kPa]	Time [s]
0	104.70	11.0
1	97.00	10.0
2	100.85	10.5
3	108.55	11.5
4	112.40	12.0
5	97.00	10.0
6	97.00	10.0
7	108.55	11.5
8	97.00	10.0
9	104.70	11.0
10	104.70	11.0
11	100.85	10.5
12	97.00	10.0
13	100.85	10.5
14	100.85	10.5
15	97.00	10.0
16	100.85	10.5
17	97.00	10.0
18	97.00	10.0
19	100.85	10.5
20	100.85	10.5
21	97.00	10.0
22	97.00	10.0
23	97.00	10.0
24	97.00	10.0
25	97.00	10.0
26	108.55	11.5
27	97.00	10.0
28	97.00	10.0
29	100.85	10.5

Appendix D

Functions of the Material Criterion

The functions used in the Material Criterion along with a description of the function are displayed in Table D.1.

Table D.1: A table displaying the functions in the Material Criterion along with basic descriptions

Name:	Description:
getVolume(d,l,w)	Volume calculator using combined shapes
getMass(P,V)	Mass calculator using Ideal Gas Law
getMass_mdot(m_dot,m1,t)	Mass calculator using mass loss rate
getMassDot(PM,P1,P2,l,w)	Mass loss rate calculator using permeability
Permeability_Poly(Temp)	Permeability calculator using experimental data
getPressure(m,V)	Pressure calculator using Ideal Gas Law
getBarlowPressure(Stress,D)	Pressure calculator using Barlow's Formula
getIdealVolume(m,P)	Volume calculator using Ideal Gas Law
getStress(d,P)	Stress calculator ussing Barlow's Formula
getStrain(sigma,t,E1,E2)	Strain calculator using HK constitutive model
getLength(l,Eta)	Length calculator using strain
getWidth(l,Eta)	Width calculator using strain
RoundOFF(a)	Make variables a float & rounds of to 3 digits
Convert(b,num)	Converts a list using RoundOFF
SaveValuesE(...)	Saves Inflation Model & ReductionInVoid Model values in lists
SaveValuesB(...)	Saves Burst Model values in lists
SaveValuesSR(...)	Saves StressRelaxation Model values in lists
SaveValuesPM(...)	Saves Permeability Model values in lists
CreateGraphs(...)	General function for creating graphs
GenerateComparisons(...)	Receives input from different models and calls CreateGraphs

Table D.1 continued from previous page

Name:	Description:
FormatFunc(value, n)	Converts values to a string for graph purposes
reset2Zero(E1,E2)	Receives moduli properties and calculates uninflated conditions
reset2Inflation(E1,E2)	Receives moduli properties and calculates inflated conditions
FixInflationModel(E1,E2)	Inflation model, as described in Section 6.2.3
ReductionInVoidModel(E1,E2)	Reduction in Void model, as described in Section 6.3.1
PermeabilityModel(Permeability, Temperature,E1,E2)	Permeability model, as described in Section 6.4.1
StressRelaxationModel(TimeMax ,E1,E2)	Stress Relaxation model, as described in Section 6.5.1
BurstModel(BurstTime, BurstPressure,E1,E2)	Burst model, as described in Section 6.6.1
CallInflation(...)	Randomizes moduli properties, calls FixInflationModel & determines candidate properties
CallReductionInVoid(...)	Randomizes moduli properties, calls ReductionInVoidModel & determines candidate properties
CallPermeability(...)	Randomizes permeation, temperature & moduli properties, calls PermeabilityModel & determines candidate properties
CallStressRelaxation(...)	Randomizes moduli properties & max time, calls StressRelaxationModel & determines candidate properties
CallBurst(...)	Randomizes moduli properties, burst pressure & burst time, calls BurstModel & determines candidate properties
MonteCarloSimulation(n, Model,ComparisonType)	Receives number of iterations, model type & graph type, then calls the different "Call-model" functions
CrossCorrelation(...)	Creates 2D histograms showing correlations between properties
Histogram(...)	Creates 1D histograms
Plot3D(...)	Creates 3D plots
Statistics(...)	Prints the candidates properties statistics
AllGraphsFunc(...)	Calls CrossCorrelation, Histogram, Plot3D, Statistics all at once.

Figure D.1, Figure D.2, Figure D.3 and Figure D.4 show the flow diagram of the "Call" functions explains in Chapter 7.

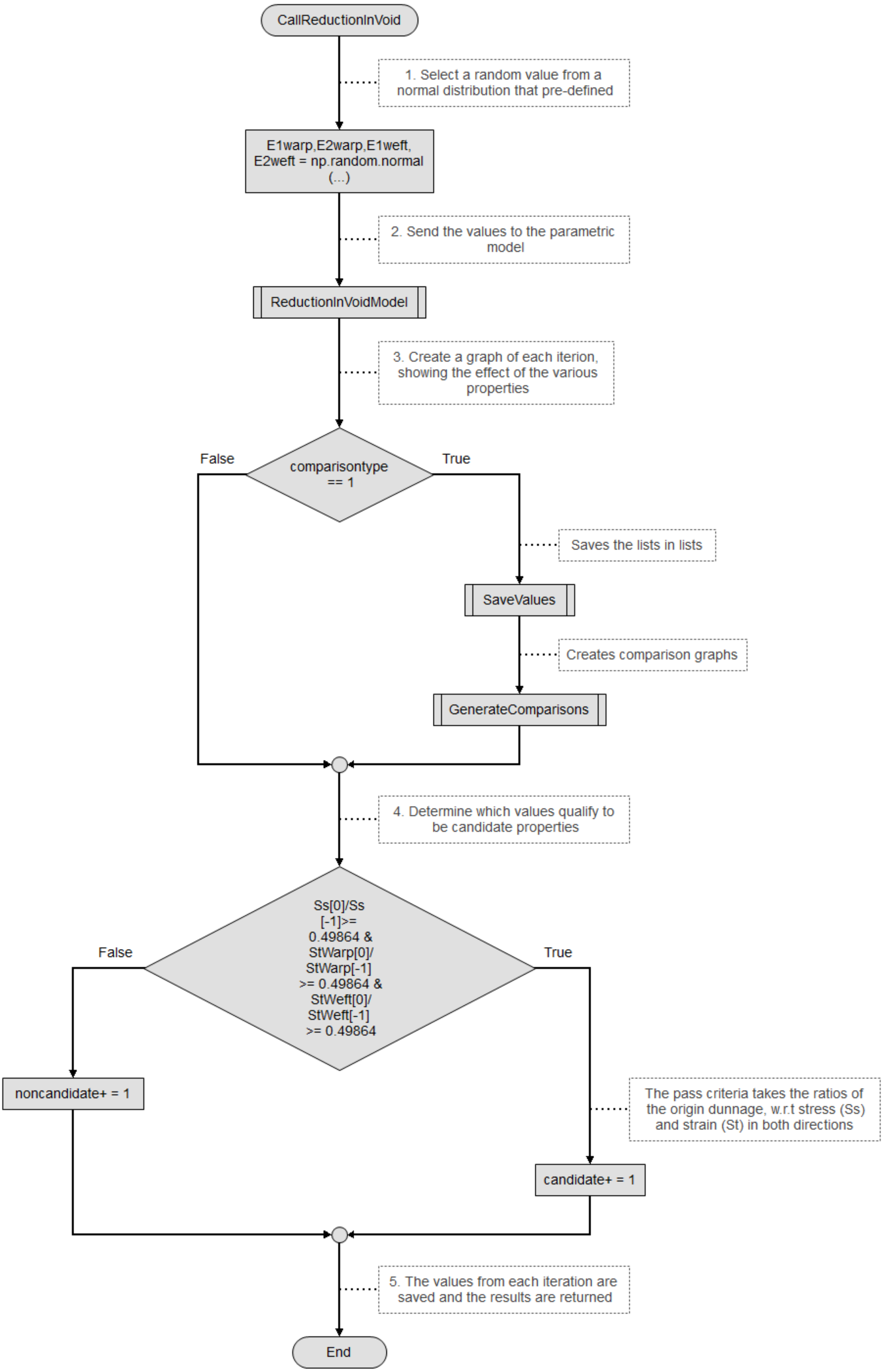


Figure D.1: A flow diagram of the CallReductionInVoid function algorithm

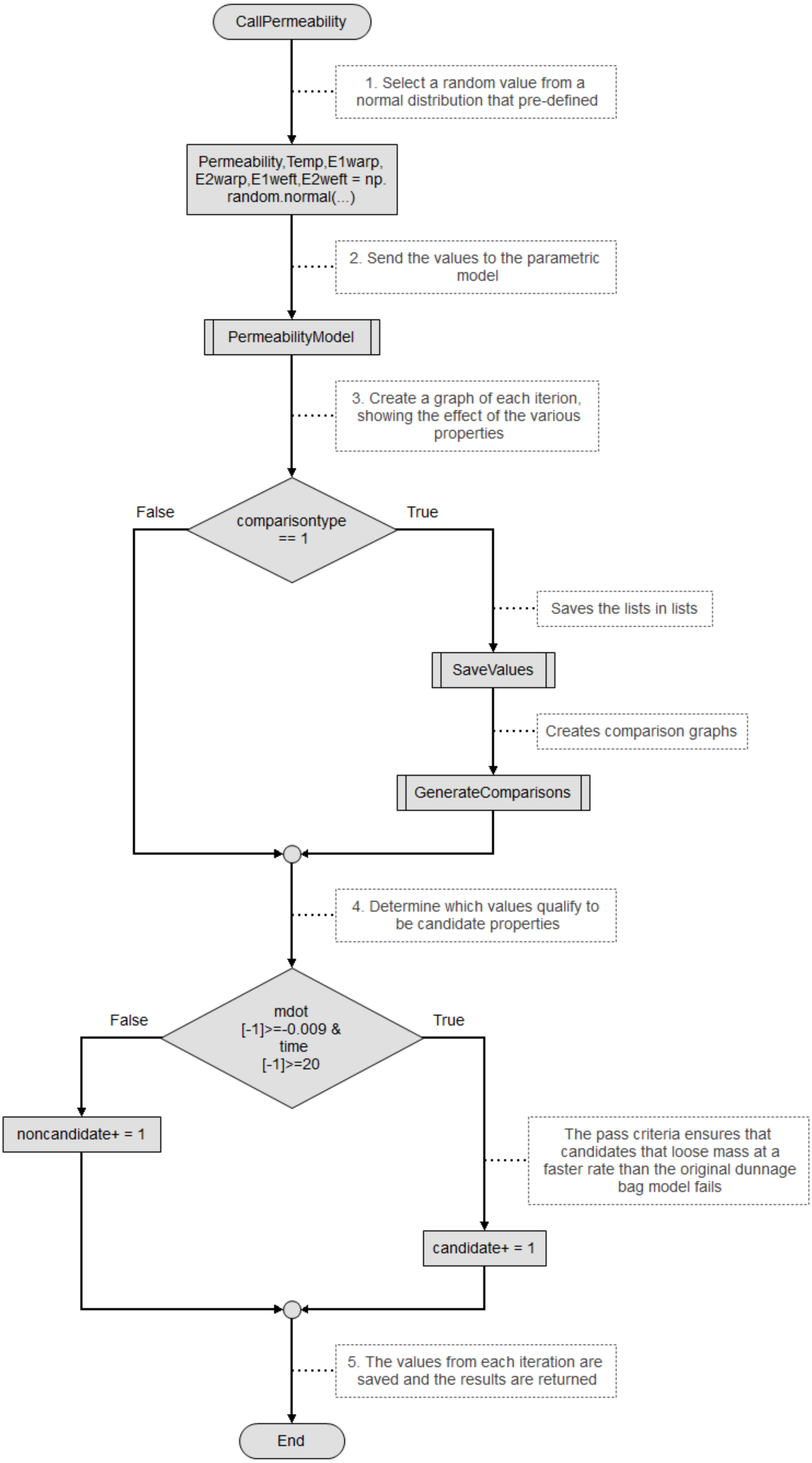


Figure D.2: A flow diagram of the CallPermeability function algorithm

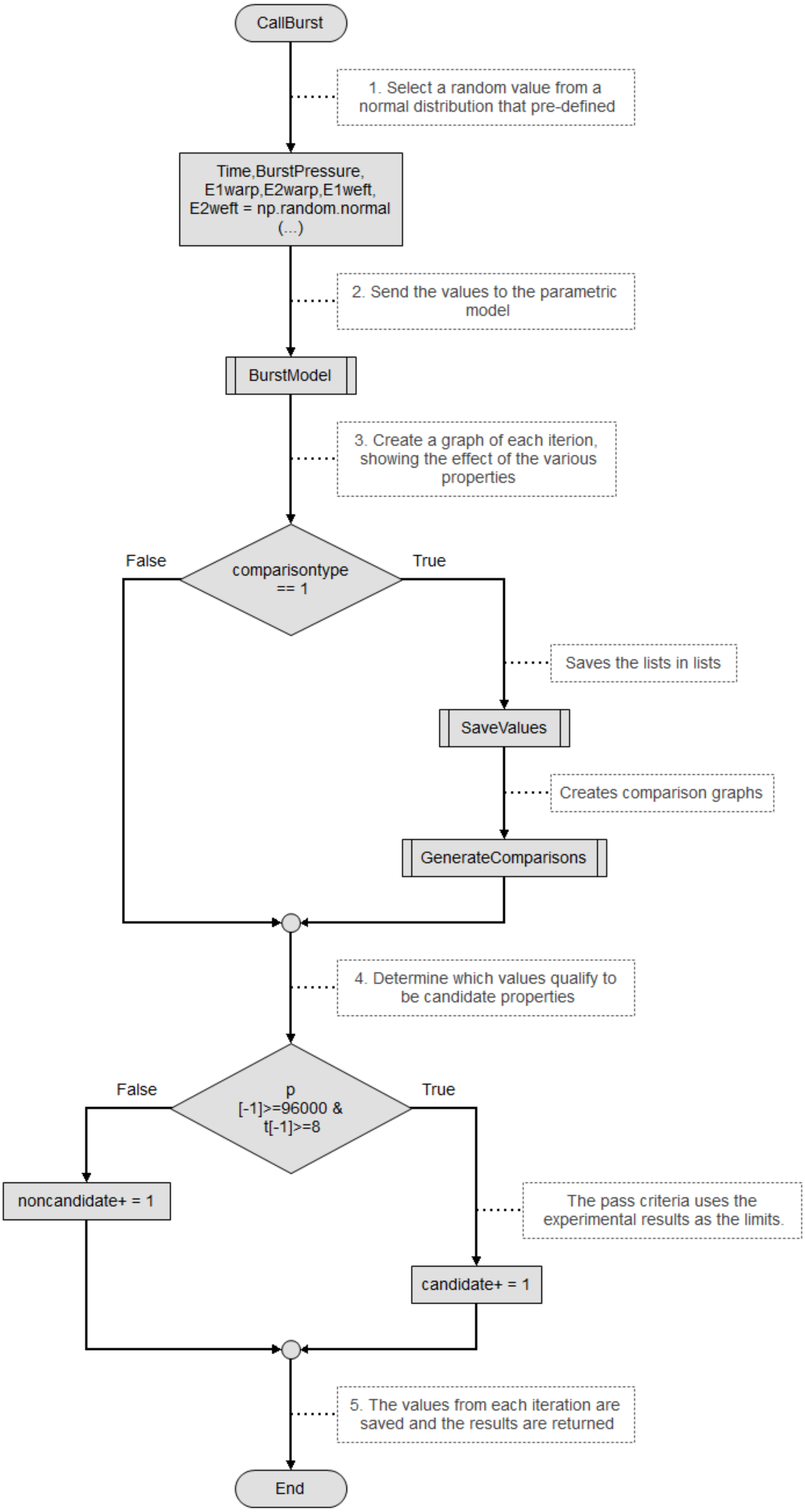


Figure D.3: A flow diagram of the CallBurst function algorithm

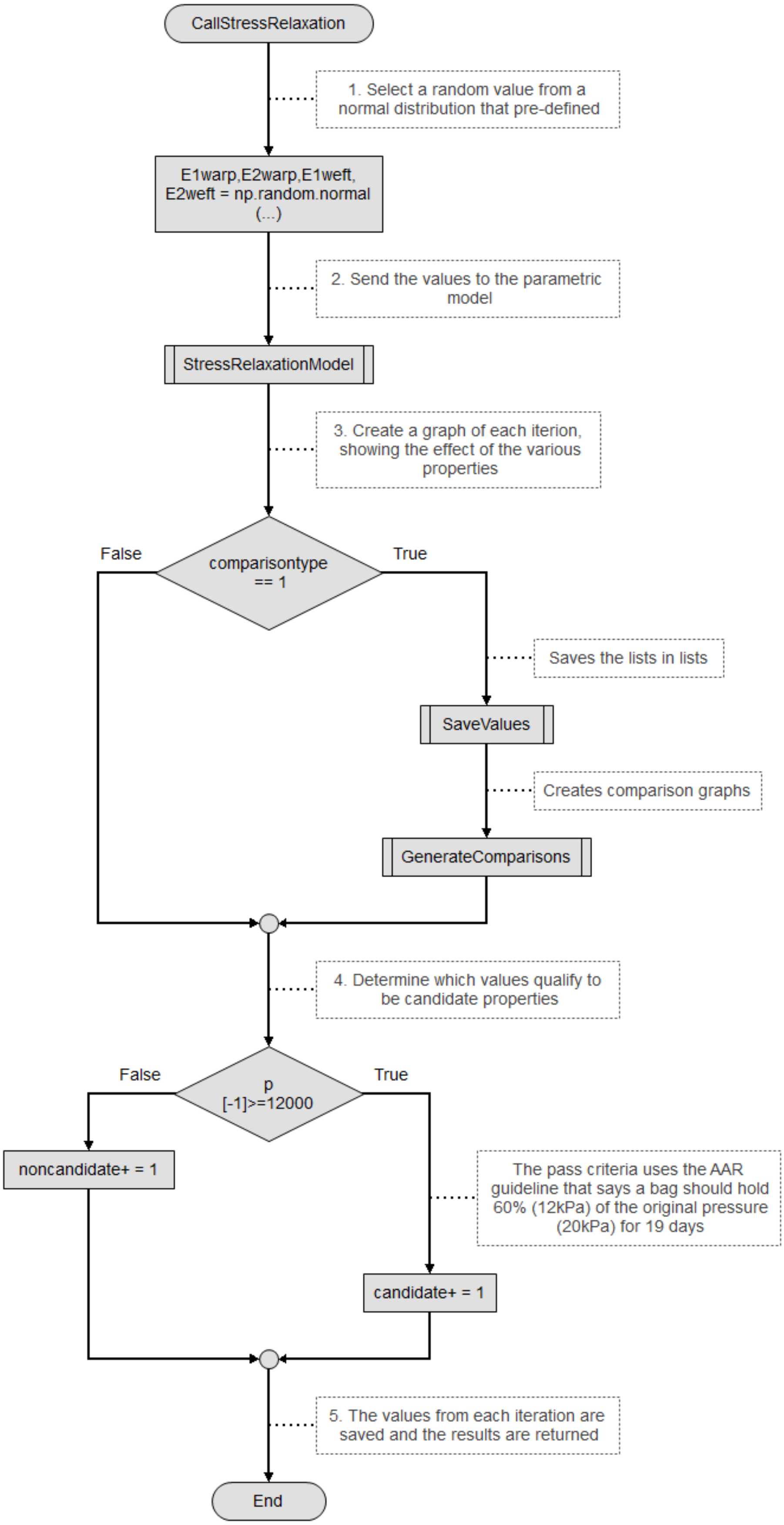


Figure D.4: A flow diagram of the CallStressRelaxation function algorithm

Appendix E

Data Processing Algorithm

This project involved extensive data handling, thus it was suited to create an algorithm on Jupyter Notebook that automatically processes the raw data. As seen in Figure E.1, the specific libraries are imported, then the folder path is specified and the raw data files are opened. From there the data is filtered as required and the various functions, specifically for the large-scale experimental data, are called to generate the comparison curves. The final image is then saves and the processes data is save to an output .txt file such that it can be called by another function again.

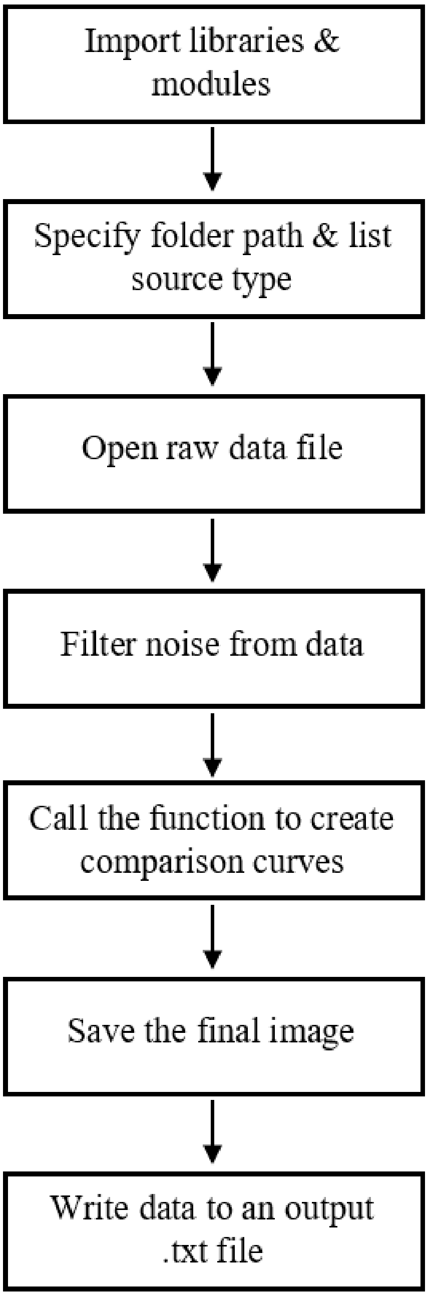


Figure E.1: Data Processing Alogrithm

Appendix F

Material Criterion Coding

The next few pages show the coding of the material criterion.

Double-Layer Dunnage Bag Material Criterion Model: Monte Carlo Simulation

STEP 1: Choose what model you want to run: 1 - Inflation Model 2 - Reduction in Void Model 3 - Permeability Model 4 - Stress Relaxation Model 5 - Burst Model Type 1,2,3,4 or 5 & press Enter

In [ ]:
```
Model=int(input())
```

STEP 2: Choose whether you want to run 20 or 10 000 iterations: 1 - To get better graphs showing the comparison between parameters, using 20 iterations 2 - To get better Monte Carlo Simulation results & Histogram graphs & model restrictions, 10 000 iterations Type 1 or 2 & press Enter

In [ ]:
```
ComparisonType=int(input())
```

In [ ]:
```
if ComparisonType == 1:
    sim_it = 1
    print("20 iterations about to run")
elif ComparisonType == 2:
    sim_it = 10000
    print("10 000 iterations about to run, please be patient...")
```

STEP 3: The program will automatically do the rest. Scroll to the heading "Main" at the bottom. Wait a few seconds... and see the results.

Libraries:

In [ ]:
```
import pandas as pd
import numpy as np
import scipy as sp
from math import pi
import matplotlib.pyplot as plt
import mpl_toolkits.mplot3d.axes3d as axes3d
import random
import seaborn as sns
import itertools
from matplotlib.ticker import MaxNLocator
% matplotlib inline
```

Global Variables:

In [ ]:
```
global R,P_atm,T,M,thickness,PM
global L_list,W_list,D_list,E1_list,E2_list,P_list,V_list,M_list,SS_list,ST_list,MDOT_list,TIME_list
,TEMP_LIST,PERM_list
global P_mdot,P_mass,P_pressure,P_time,P_Temp,P_PM
global A,B,C,D,E,F,G,H,K,L

A,B,C,D,E,F,G,H,K,L=np.empty((sim_it, 0)).tolist(),np.empty((sim_it, 0)).tolist(),np.empty((sim_it,
0)).tolist(),np.empty((sim_it, 0)).tolist(),np.empty((sim_it, 0)).tolist(),np.empty((sim_it, 0)).tol
ist(),np.empty((sim_it, 0)).tolist(),np.empty((sim_it, 0)).tolist(),np.empty((sim_it, 0)).tolist(),n
p.empty((sim_it, 0)).tolist()
P_mdot,P_mass,P_pressure,P_time,P_Temp,P_PM=[],[],[],[],[],[]
L_list,W_list,D_list,E1_list,E2_list,P_list,V_list,M_list,SS_list,ST_list,Ti_list = np.empty((sim_it
, 0)).tolist(),np.empty((sim_it, 0)).tolist(),np.empty((sim_it, 0)).tolist(),np.empty((sim_it, 0)).t
olist(),np.empty((sim_it, 0)).tolist(),np.empty((sim_it, 0)).tolist(),np.empty((sim_it, 0)).tolist
(),np.empty((sim_it, 0)).tolist(),np.empty((sim_it, 0)).tolist(),np.empty((sim_it, 0)).tolist(),np.e
mpty((sim_it, 0)).tolist()
R = 8.3144598 #Gas constant for air [1/K.mol]
```

```
P_atm = 101325 #Atmospheric pressure [Pa]
T = 20 + 273.13 #Temperature [K]
M = 28.96 #Molar mass of air [g/mol]
thickness = 0.042*10**-3 #Thickness of membrane [m]
PM = 1.846*10**-10
```

Functions:

In [ ]:
```
def getVolume(d,l,w):
    LengthLong = w - float(pi*d)/2
    LengthShort = l - float(pi*d)/2
    AreaLong = d*LengthLong + float(pi*d**2)/4
    VolumeSphere = float(1/6)*(d**3)*(pi)
    return (AreaLong*LengthShort) + 4*VolumeSphere
```

In [ ]:
```
def getMass(P,V):
    return((M*(P+P_atm)*V)/(R*T))
```

In [ ]:
```
def getMass_Permeability(m_dot,m1,t):
    return m_dot*t + m1
```

In [ ]:
```
def getMassDot(PM,P1,P2,l,w):
    A = l*w
    return ((PM*(P2-P1)*A/thickness))#*10000
```

In [ ]:
```
def Permeability_Poly(Temp):
    return  (4.9425*10**-3 *(Temp+273.15)**2 + -2.90454275 *(Temp+273.15) + 4.28143218*10**2 )*10**-
10
```

In [ ]:
```
def getPressure(m,V):
    return((m/M)*R*T/(V))-P_atm
```

In [ ]:
```
def getBarlowPressure(Stress,D):
    return (2*Stress*thickness/D)
```

In [ ]:
```
def getIdealVolume(m,P):
    return((m/M)*R*T)/(P+P_atm)
```

In [ ]:
```
def getStress(d,P):
    return (d*P)/(2*thickness)
```

In [ ]:
```
def getStrain(sigma,t,E1,E2):
    N2 = -140150.76595634609
    return (sigma*10**-6)*((1/E1)+((1/E2)*(1-np.exp(E2*t/N2))))
```

In [ ]:
```
def getLength(l,Eta):
    return l +(l*Eta)
```

In [ ]:
```
def RoundOFF(a):
    return float(format(a, '.3f'))
```

In [ ]:
```
def Convert(b,num): #Converts units from SI to easy-readable units
    return[ RoundOFF(x * num) for x in b]
```

In [ ]:
```
def SaveValuesE(length,width,diameter,e1,e2,Pressure,Volume,mass,Stress,Strain,i): #save values in l
ists
    L_list[i],W_list[i],D_list[i],E1_list[i],E2_list[i],P_list[i],V_list[i],M_list[i],SS_list[i],ST_
list[i] = length,width,diameter,e1,e2,Pressure,Volume,mass,Stress,Strain
    return L_list,W_list,D_list,E1_list,E2_list,P_list,V_list,M_list,SS_list,ST_list
```

In [ ]:
```
def SaveValuesB(Volume,Stress,Strain,length,width,time,Pressure,diameter,e1,e2,i): #save values in l
ists
    L_list[i],W_list[i],D_list[i],E1_list[i],E2_list[i],P_list[i],V_list[i],SS_list[i],ST_list[i],Ti
_list[i] = length,width,diameter,e1,e2,Pressure,Volume,Stress,Strain,time
    return L_list,W_list,D_list,E1_list,E2_list,P_list,V_list,SS_list,ST_list,Ti_list
```

In [ ]:
```
def SaveValuesSR(w,l,d,ss,t,p,st,v,i):#save values in list
    W_list,L_list,D_list,SS_list,TIME_list,P_list,ST_list,V_list =w,l,d,ss,t,p,st,v
    return W_list,L_list,D_list,SS_list,TIME_list,P_list,ST_list,V_list
```

In [ ]:
```
def SaveValuesPM(mdot,m,p,ti,te,pm,i):#save values in list
    MDOT_list,M_list,P_list,TIME_list,TEMP_list,PERM_list = mdot,m,p,ti,te,pm
    return MDOT_list,M_list,P_list,TIME_list,TEMP_list,PERM_list
```

In [ ]:
```
#Create Figures
def CreateGraphs(x,y,xname,yname,label,title,i,axname):
    labels = label
    axis_font = {'size':'12'} #customize graph
    plt.xlabel(xname,**axis_font),plt.ylabel(yname,**axis_font) #name axes
    axname.scatter(x, y, label=labels) #create a scatter plot
    axname.legend(loc='center left',bbox_to_anchor=(1,0.5),title = title)
    return
```

In [ ]:
```
def GenerateComparisons(model,legend_title, A,B,C,D,E,F,G,H,K,L,A_label,B_label,C_label,D_label,E_la
bel,F_label,G_label,H_label,K_label,L_label,j):

    #InflationModel Comparisons:
    if model == 1:
        CreateGraphs(F[j],E[j],F_label,E_label,(int(K),int(L)),legend_title,j,ax1) #Length vs Diamet
er
        CreateGraphs(E[j],A[j],E_label,A_label,(int(K),int(L)),legend_title,j,ax2) #Diameter vs Pres
sure
        CreateGraphs(G[j],F[j],G_label,F_label,(int(K),int(L)),legend_title,j,ax3) #Width vs Length
        CreateGraphs(D[j],A[j],D_label,A_label,(int(K),int(L)),legend_title,j,ax4) #Volume vs Pressu
re

    #ReductionInVoidModel Comparisons:
    if model ==2:
        CreateGraphs(E[j],A[j],E_label,A_label,(int(K),int(L)),legend_title,j,ax1) #Diameter vs Pres
sure
        CreateGraphs(E[j],B[j],E_label,B_label,(int(K),int(L)),legend_title,j,ax2) #Diameter vs Stre
ss
        CreateGraphs(C[j],B[j],C_label,B_label,(int(K),int(L)),legend_title,j,ax3) #Strain vs Stress
        CreateGraphs(D[j],A[j],D_label,A_label,(int(K),int(L)),legend_title,j,ax4) #Volume vs Pressu
re

    #PermeabilityModel Comparisons:
    if model == 3:
        CreateGraphs(B,C,B_label,C_label,(F,E),legend_title,j,ax1) #mass vs Pressure
        CreateGraphs(A,C,A_label,C_label,(F,E),legend_title,j,ax2) #mass loss rate vs Pressure
        CreateGraphs(D,C,D_label,C_label,(F,E),legend_title,j,ax3) #time vs Pressure
        CreateGraphs(D,B,D_label,B_label,(F,E),legend_title,j,ax4) #time vs mass
```

```
    #BurstModel Comparisons:
    if model == 5:
        CreateGraphs(L,E,L_label,E_label,(int(L[-1]),int(D[-1])),legend_title,j,ax1) #Pressure vs Di
ameter
        CreateGraphs(L,G,L_label,G_label,(int(L[-1]),int(D[-1])),legend_title,j,ax2) #time vs Pressu
re
        CreateGraphs(L,D,L_label,D_label,(int(L[-1]),int(D[-1])),legend_title,j,ax3) #Pressure vs Ti
me
        CreateGraphs(L,D,L_label,D_label,(int(L[-1]),int(D[-1])),legend_title,j,ax4) #time vs Stress
    return
```

In [ ]:
```
def FormatFunc(value, n):#converts value to string for graph purposes
    if n == 0:
        return "Fail"
    elif n == 1:
        return "Pass"
    return
```

Initial Values:

In [ ]:
```
def reset2Zero(E1,E2):
    #Bag dimensions:
    length = 1.7 #[m]
    width = 0.85 #[m]
    diameter = 0.01#[m]

    #Assign initial values:
    Pressure = [1000] #Gauge Pressure inside dunnage bag [Pa]
    Volume = [0.0125] #Volume of dunnage bag [m3]
    mass = getMass(Pressure[0],Volume[0]) #Mass of air inside dunnage bag [g]
    Stress = [getStress(diameter,Pressure[0])]
    Strain = [getStrain(Stress[0],0,E1,E2)]

    return length,width,diameter,Pressure,Volume,mass,Stress,Strain
```

In [ ]:
```
def reset2Inflation(E1,E2):
    #Call InflationModel:
    Pressure,Stress,Strain,Volume,Diameter,Length,Width,Mass,E1,E2 = FixInflationModel(E1,E2)
    #Take last value from the list:
    length,width,diameter,pressure,volume,mass,stress,strain = Length[-1],Width[-1],Diameter[-1],[Pr
essure[-1]],[Volume[-1]],Mass[-1],[Stress[-1]],[Strain[-1]]
    return length,width,diameter,pressure,volume,mass,stress,strain
```

Models:

In [ ]:
```
def FixInflationModel(E1,E2):

    length,width,diameter,Pressure,Volume,mass,Stress,Strain = reset2Zero(E1,E2) #reset the initial
 values
    Diameter,Mass,Length,Width=[diameter],[mass],[length],[width]
    i=0

    while diameter <= 0.31:

        Pressure.append(int(getPressure(mass,Volume[i]))) #get PRESSURE of dunnage bag from IDEAL GA
S LAW
```

```
        Stress.append(getStress(diameter,(Pressure[i+1]))) #get STRESS from BARLOWS FORMULA

        Strain.append(getStrain(Stress[i+1],5,E1,E2)) #get STRAIN from HK MODEL

        Length.append(getLength(1.7,Strain[i+1])) #get LENGTH from STRAIN FORMULA

        Width.append(getLength(0.85,Strain[i+1])) #get WIDTH from STRAIN FORMULA

        Volume.append(getVolume(diameter,Length[i+1],Width[i+1])) #get VOLUME of dunnage bag from GE
OMETERY

        Diameter.append(diameter)

        Mass.append(mass)

        diameter+=0.01

        mass+=13.9

        i+=1
    del Pressure[0:8],Stress[0:8],Strain[0:8],Volume[0:8],Diameter[0:8],Length[0:8],Width[0:8],Mass[
0:8] #delete the first 8 values because model is still converging
    return [Pressure,Stress,Strain,Volume,Diameter,Length,Width,Mass,E1,E2]
```

In [ ]:
```
#Pressure,Stress,Strain,Volume,Diameter,Length,Width,Mass,E1,E2=FixInflationModel(3711.626220070187
6,4310.134748557914 5)
#print("Pressure",Pressure,"\n\n","Stress",Stress,"\n\n","Strain",Strain,"\n\n","Volume",Volume,"\n
\n","Diameter",Diameter,"\n\n","Mass",Mass,"\n\n","Length",Length,"\n\n","Width",Width,"\n\n\n",E1)
```

In [ ]:
```
def ReductionInVoidModel(E1,E2):

    length,width,diameter,Pressure,Volume,mass,Stress,Strain = reset2Inflation(E1,E2)
    Diameter,Mass,Length,Width=[diameter],[mass],[length],[width]
    i = 0

    while diameter >= 0.180:

        Volume.append(getVolume(diameter,Length[i],Width[i])) #get VOLUME of dunnage bag from GEOMET
ERY

        Pressure.append(getPressure(Mass[i],Volume[i+1])) #get PRESSURE of dunnage bag from IDEAL GA
S LAW

        Stress.append(getStress(diameter,(Pressure[i+1]))) #get STRESS from BARLOWS FORMULA

        Strain.append(getStrain(Stress[i+1],277,E1,E2)) #get STRAIN from HK MODEL

        Length.append(getLength(1.7378,Strain[i+1])) #get LENGTH from STRAIN FORMULA

        Width.append(getLength(0.8689,Strain[i+1])) #get WIDTH from STRAIN FORMULA

        Mass.append(418.29) #mass is assumed to remain constant

        Diameter.append(diameter)

        diameter-=0.001 #m

        i+=1

    del Pressure[0:8],Stress[0:8],Strain[0:8],Volume[0:8],Diameter[0:8],Length[0:8],Width[0:8],Mass[
0:8] #delete the first 8 values because model is still converging
    return [Pressure,Stress,Strain,Volume,Diameter,Length,Width,Mass,E1,E2]
```

```
In [ ]: #Pressure,Stress,Strain,Volume,Diameter,Length,Width,Mass,E1,E2=ReductionInVoidModel(3711.6262200701
876,4310.1347485579145)
#print("Pressure",Pressure,"\n\n","Stress",Stress,"\n\n","Strain",Strain,"\n\n","Volume",Volume,"\n
\n","Diameter",Diameter,"\n\n","Mass",Mass,"\n\n","Length",Length,"\n\n","Width",Width,"\n\n\n",E1)
```

```
In [ ]: def PermeabilityModel(Permeability,Temperature,E1,E2): #No change in volume, just mass loss

    length,width,diameter,pressure,Volume,mass,Stress,Strain = reset2Inflation(E1,E2)
    mass=mass*0.001 #convert from g to kg
    print(length,width,diameter,pressure,Volume,mass,Stress,Strain)
    Mass,MassDot,time,pressure,i,i_max = [mass],[-0.005],0,pressure[0],0,61     #kg, kg/hr,hr,Pa
    Time,Pressure = [time],[pressure] #hr,Pa

    while Mass[i] > 0  and Pressure[i] > 0 and Time[i] < 60 and i < i_max:

        MassDot.append(getMassDot(Permeability,Pressure[i],(Pressure[i]-700),length,width)) #kg/hr

        Mass.append(getMass_Permeability(MassDot[i],Mass[i],Time[i])) #kg (hr)

        Pressure.append(pressure)

        Time.append(time) #hr

        pressure-=2900

        time+=3 #hr

        i+=1
    del MassDot[-1],Mass[-1],Pressure[-1],Time[-1] #del the last entry since the mass tends to a neg
ative number within the loop
    return [MassDot,Mass,Pressure,Time,Temperature,Permeability]
```

```
In [ ]: #MassDot,Mass,Pressure,Time,Temperature,Permeability=PermeabilityModel(1.846*10**-10,20) #No change
 in volume, just mass loss
#print("MassDot",MassDot,"\n\n","Mass",Mass,"\n\n","Pressure",Pressure,"\n\n","Time",Time,"\n\n","Te
mperature",Temperature,"\n\n","Permeability",Permeability,"\n\n\n")
```

```
In [ ]: def StressRelaxationModel(TimeMax,E1,E2):   #Constant strain with decreasing stress, no mass loss
    #leave out TimeMax
    length,width,diameter,Pressure,Volume,mass,stress,Strain = reset2Inflation(E1,E2)
    time,i,i_max,stress,mass=0,0,500,stress[0],428
    print(mass)
    Width,Length,Diameter,Time,Stress=[width],[length],[diameter],[time],[stress]


    while i < i_max and time <= TimeMax:

        Pressure.append(getPressure(mass,Volume[i])) #get PRESSURE of dunnage bag from IDEAL GAS LAW

        Strain.append(Strain[0]) #append strain such that dataframe have equal number of entries

        Volume.append(getVolume(Diameter[i],Length[i],Width[i])) #get VOLUME of dunnage bag from GEO
METERY

        Stress.append(getStress(diameter,(Pressure[i+1]))) #get STRESS from BARLOWS FORMULA

        Diameter.append(diameter)

        Time.append(time)

        Length.append(length)
```

```
        Width.append(width)

        diameter-=0.00020085 #stay same

        length+=0.000427

        width+=0.000427

        time+=1

        i+=1
    del Pressure[0:1],Stress[0:1],Strain[0:1],Volume[0:1],Diameter[0:1],Length[0:1],Width[0:1],Time[
0:1] #delete the first 4 values because model
    return [Pressure,Volume,Length,Width,Diameter,Time,Stress,Strain]
```

In [ ]:
```
Pressure,Volume,Length,Width,Diameter,Time,Stress,Strain=StressRelaxationModel(456,3711.626,4310.135
)
#print("Pressure",Pressure,"\n\n","Volume",Volume,"\n\n","Length",Length,"\n\n","Width",Width,"\n
\n","Diameter",Diameter,"\n\n","Time",Time,"\n\n","Stress",Stress,"\n\n","Strain",Strain,"\n\n\n")
```

In [ ]:
```
def BurstModel(BurstTime,BurstPressure,E1,E2):
    length,width,diameter,pressure,Volume,mass,Stress,Strain = reset2Inflation(E1,E2)
    pressure,time,i=pressure[0],0,0
    Pressure,Length,Width,Diameter,Time=[20000],[length],[width],[0.4],[time]

    while i<20 and Pressure[i] <= 90000 and Time[i] <= 20:

        Volume.append(getVolume(Diameter[i],Length[i],Width[i])) #get VOLUME of dunnage bag from GEO
METERY

        Pressure.append(getPressure(mass,Volume[i+1])) #get PRESSURE of dunnage bag from IDEAL GAS L
AW

        Stress.append(getStress(Diameter[i],(Pressure[i]))) #get STRESS from BARLOWS FORMULA

        Strain.append(getStrain(Stress[i+1],8,E1,E2)) #get STRAIN from HK MODEL

        Length.append(getLength(length,Strain[i+1])) #get LENGTH from STRAIN FORMULA

        Width.append(getLength(width,Strain[i+1])) #get WIDTH from STRAIN FORMULA

        Time.append(time)

        Diameter.append(diameter)

        if i<4:

            time+=0 #to account for iteration convergence in loop

        if i>=4:

            time+=0.6 #s

        diameter-=0.00880 #m

        i+=1

    del Pressure[0:5],Stress[0:5],Strain[0:5],Volume[0:5],Diameter[0:5],Length[0:5],Width[0:5],Time[
0:5] #delete the first 4 values because model is still converging
    return [Volume,Stress,Strain,Length,Width,Time,Pressure,Diameter,E1,E2]
```

In [ ]:
```
#Volume,Stress,Strain,Length,Width,Time,Pressure,Diameter,E1,E2=BurstModel(8,92000,3711.626,4310.134
7)
#print("Volume",Volume,"\n\n","Stress",Stress,"\n\n","Strain",Strain,"\n\n","Length",Length,"\n
\n","Width",Width,"\n\n","Time",Time,"\n\n","Pressure",Pressure,"\n\n","Diameter",Diameter,"\n\n","E
1",E1,"\n\n","E2",E2,"\n\n\n\n")
```

Monte Carlo Simulation:

In [ ]:
```
def CallInflation(comparisontype,ll,ww,dd,ee1,ee2,pp,vv,mm,sss,sst,PASS_FAIL,candidate,NONcandidate,c
ounter):

    # 1a. Randomize the E1 and E2 input:
    E1_original, SD1 = 3711.626, 3711.626*0.1 #mean and standard deviation
    E2_original, SD2 = 4310.135, 4310.135*0.1 #mean and standard deviation
    E1,E2 = np.random.normal(E1_original, SD1), np.random.normal(E2_original, SD2 )


    #2. Send random values of E1 and E2:
    p,ss,st,v,d,l,w,m,e1,e2 = FixInflationModel(E1,E2) #returns list of each variable


    # 3. Creat a graph of each iteration for all E1 & E2:
    if comparisontype == 1:
        L_list,W_list,D_list,E1_list,E2_list,P_list,V_list,M_list,SS_list,ST_list = SaveValuesE(l,w,d
,E1,E2,Convert(p,10**-3),v,m,ss,st,counter) #append values into lists
        GenerateComparisons(1,"(E1,E2)",P_list,SS_list,ST_list,V_list,D_list,L_list,W_list,M_list,E1,
E2,"Pressure","Stress","Strain","Volume","Diameter","Length","Width","Mass","E1","E2",counter)


    # 4 .Determine which values of E1 and E2 are candidate properties:
    if ss[-1] <= 747821423 and st[-1] <= 0.0226:
        candidate +=1
        #print("PASS")
        PASS_FAIL.append(1)
    else:
        NONcandidate +=1
        #print("FAIL")
        PASS_FAIL.append(0)


    # 5. Append last value from InflationModel iteration:
    ll.append(l[-1]),ww.append(w[-1]),dd.append(d[-1]),ee1.append(E1),ee2.append(E2),pp.append(p[-1
]),vv.append(v[-1]),mm.append(m[-1]),sss.append(ss[-1]),sst.append(st[-1])

    return candidate,NONcandidate,PASS_FAIL,ll,ww,dd,ee1,ee2,pp,vv,mm,sss,sst
```

In [ ]:
```
def CallReductionInVoid(comparisontype,ll,ww,dd,ee1,ee2,pp,vv,mm,sss,sst,PASS_FAIL,candidate,NONcandi
date,counter):

    # 1. Randomize the E1 and E2 input:
    E1_original, SD1 = 3711.626, 3711.626*0.1 #mean and standard deviation
    E2_original, SD2 = 4310.135, 4310.135*0.1 #mean and standard deviation
    E1,E2 = np.random.normal(E1_original, SD1), np.random.normal(E2_original, SD2 )


    # 2. Send random values of E1 and E2:
    p,ss,st,v,d,l,w,m,e1,e2 = ReductionInVoidModel(E1,E2) #returns list of each variable
```

```
    # 3. Creat a graph of each iteration for all E1 & E2:
    if comparisontype == 1:
        L_list,W_list,D_list,E1_list,E2_list,P_list,V_list,M_list,SS_list,ST_list = SaveValuesE(l,w,d
,E1,E2,Convert(p,10**-3),v,m,ss,st,counter) #append values into lists
        GenerateComparisons(2,"(E1,E2)",P_list,SS_list,ST_list,V_list,D_list,L_list,W_list,M_list,E1,
E2,"Pressure","Stress","Strain","Volume","Diameter","Length","Width","Mass","E1","E2",counter)


    # 4 .Determine which values of E1 and E2 are candidate properties:
    if st[-1] <= 0.56 and ss[-1] <=111595840 and p[-1]<=51790 :
        candidate +=1
        #print("PASS")
        PASS_FAIL.append(1)
    else:
        NONcandidate +=1
        #print("FAIL")
        PASS_FAIL.append(0)


    # 5. Append last value from ReductionInVoidModel iteration:
    ll.append(l[-1]),ww.append(w[-1]),dd.append(d[-1]),ee1.append(E1),ee2.append(E2),pp.append(p[-1
]),vv.append(v[-1]),mm.append(m[-1]),sss.append(ss[-1]),sst.append(st[-1])

    return candidate,NONcandidate,PASS_FAIL,ll,ww,dd,ee1,ee2,pp,vv,mm,sss,sst
```

In [ ]:

```
def CallPermeability(comparisontype,p_mdot,mm,pp,p_time,p_temp,p_pm,PASS_FAIL,candidate,NONcandidate
,counter):

    # 1. Randomize Permeability, Temperature, E1 and E2 input:
    Permeability = np.random.normal(PM,PM*0.1)
    Temperature = np.random.normal(20,20*0.2)
    E1_original, SD1 = 3711.626, 3711.626*0.1 #mean and standard deviation
    E2_original, SD2 = 4310.135, 4310.135*0.1 #mean and standard deviation
    E1,E2 = np.random.normal(E1_original, SD1), np.random.normal(E2_original, SD2 )


    # 2. Send random values of Permeability:
    mdot,m,p,time,temp,pm = PermeabilityModel(Permeability,Temperature,E1,E2) #receives a list for e
ach variable


    # 3. Creat a graph of each iteration for all Permeability: save lists in lists
    if comparisontype == 1:
        MDOT_list,M_list,P_list,TIME_list,TEMP_list,PERM_list = SaveValuesPM(mdot,m,p,time,int(Tempe
rature),'{:0.3e}'.format(Permeability),counter) #append values into lists
        GenerateComparisons(3,("Permeability,Temperature"),MDOT_list,M_list,P_list,TIME_list,TEMP_li
st,PERM_list,0,0,0,0,"Mass Loss Rate","Mass","Pressure","Time","Temperature","Permeability",0,0,0,0,
counter)


    # 4.Determine which values of Permeability are candidate properties:
    if time[-1]>=21 and mdot[-1]>=-0.0066:
        candidate +=1
        #print("PASS")
        PASS_FAIL.append(1)
    else:
        NONcandidate +=1
        #print("FAIL")
        PASS_FAIL.append(0)
```

```
    # 5. Append last value from iteration:
    p_mdot.append(mdot[-1]),mm.append(m[-1]),pp.append(p[-1]),p_time.append(time[-1]),p_temp.append(
Temperature),p_pm.append(Permeability*10**10)

    return candidate,NONcandidate,PASS_FAIL,p_mdot,mm,pp,p_time,p_temp,p_pm
```

In [ ]:
```
def CallStressRelaxation(comparisontype,dd,sss,tt,ll,pp,sst,vv,ww,PASS_FAIL,candidate,NONcandidate,c
ounter):

    # 1a. Randomize the Time and BurstPressure, E1 and E2 input:
    timemax = np.random.normal(456, 456*0.1) #457 everytime
    E1_original, SD1 = 3711.626, 3711.626*0.1 #mean and standard deviation
    E2_original, SD2 = 4310.135, 4310.135*0.1 #mean and standard deviation
    E1,E2 = np.random.normal(E1_original, SD1), np.random.normal(E2_original, SD2 )


    # 2. Send random values:
    p,v,l,w,d,t,ss,st = StressRelaxationModel(timemax,E1,E2) #returns list of each variable



    # 3. Creat a graph of each iteration for all:
    if comparisontype == 1:
        W_list,L_list,D_list,SS_list,T_list,P_list,ST_list,V_list = SaveValuesSR(w,l,d,ss,t,p,st,v,c
ounter) #append values into lists
        GenerateComparisons(4,"(EndTime)",W_list,L_list,D_list,Convert(SS_list,10**-6),T_list,Conver
t(P_list,10**-3),ST_list,V_list,0,0,"Width","Length","Diameter","Stress [MPa]","Time [hrs]","Pressur
e [kPa]","Strain","Volume",0,0,counter)


    # 4 .Determine which values that are candidate properties:
    if t[-1]>= 456 and p[-1]>=12000:
        candidate +=1
        #print("PASS")
        PASS_FAIL.append(1)
    else:
        NONcandidate +=1
        #print("FAIL")
        PASS_FAIL.append(0)


    # 5. Append last value from StressRelaxationModel iteration:
    ll.append(l[-1]),ww.append(w[-1]),dd.append(d[-1]),tt.append(t[-1]),pp.append(p[-1]),vv.append(v
[-1]),sss.append(ss[-1]),sst.append(st[-1])

    return candidate,NONcandidate,PASS_FAIL,dd,sss,tt,ll,pp,sst,vv,ww
```

In [ ]:
```
def CallBurst(comparisontype,ll,ww,dd,ee1,ee2,pp,vv,sss,sst,tti,PASS_FAIL,candidate,NONcandidate,counter):

    # 1a. Randomize the BurstTime and BurstPressure and E1 and E2 input:
    Time_original, SD1 = 8, 8*0.1 #mean and standard deviation
    BurstPressure_original, SD2 = 92000, 92000*0.1 #mean and standard deviation
    Time,BurstPressure = np.random.normal(Time_original, SD1), np.random.normal(BurstPressure_original, SD
2)
    E1_original, SD1 = 3711.626, 3711.626*0.1 #mean and standard deviation
    E2_original, SD2 = 4310.135, 4310.135*0.1 #mean and standard deviation
    E1,E2 = np.random.normal(E1_original, SD1), np.random.normal(E2_original, SD2 )
```

```
    # 2. Send random values of Time and BurstPressure:
    v,ss,st,l,w,ti,p,d,e1,e2 = BurstModel(Time,BurstPressure,E1,E2) #returns list of each variable


    # 3. Creat a graph of each iteration for all Time & BurstPressure:
    if comparisontype == 1:
        L_list,W_list,D_list,E1_list,E2_list,P_list,V_list,SS_list,ST_list,T_list = SaveValuesB(v,ss,st,l,
w,ti,p,d,e1,e2,counter) #append values into lists
        GenerateComparisons(5,"(t, p)",L_list[counter],W_list[counter],D_list[counter],Convert(P_list[coun
ter],10**-3),V_list[counter],Convert(SS_list[counter],10**-6),ST_list[counter],int(E1),int(E2),T_list[coun
ter],"Length","Width","Volume [m^3]","Pressure [kPa]","Void size [m]","Stress [MPa]","Strain","E1","E2","T
ime [s]",counter)


    # 4 .Determine which values of Time and BurstPressure are candidate properties:
    if ti[-1] >= 8 and p[-1]> 88000:
        candidate +=1
        #print("PASS")
        PASS_FAIL.append(1)
    else:
        NONcandidate +=1
        #print("FAIL")
        PASS_FAIL.append(0)

    #print(ti[-1],p[-1])
    # 5. Append last value from BurstModel iteration:
    ll.append(l[-1]),ww.append(w[-1]),dd.append(d[-1]),eel.append(E1),ee2.append(E2),tti.append(RoundOFF(T
ime)),pp.append(int(BurstPressure)),vv.append(v[-1]),ee2.append(E2),sss.append(ss[-1]),sst.append(st[-1])
    return candidate,NONcandidate,PASS_FAIL,ll,ww,dd,eel,ee2,pp,vv,sss,sst,tti
```

```
In [ ]: def MonteCarloSimulation(n,Model,ComparisonType): #n is the number of times that the simulation is r
un
    candidate,NONcandidate,counter = 0,0,0
    np.random.seed(0)
    PASS_FAIL,ll,ww,dd,eel,ee2,pp,vv,mm,sss,sst,t,tt=[],[],[],[],[],[],[],[],[],[],[],[],[]
    p_mdot,p_time,p_temp,p_pm = [],[],[],[]

    for _ in itertools.repeat(None, n):

        if Model == 1:      #INFLATION MODEL
            candidate,NONcandidate,PASS_FAIL,ll,ww,dd,eel,ee2,pp,vv,mm,sss,sst = CallInflation(Compa
risonType,ll,ww,dd,eel,ee2,pp,vv,mm,sss,sst,PASS_FAIL,candidate,NONcandidate,counter)
            variables = ll,ww,dd,eel,ee2,pp,vv,mm,sss,sst

        if Model == 2:      #REDUCTION IN VOID MODEL
            candidate,NONcandidate,PASS_FAIL,ll,ww,dd,eel,ee2,pp,vv,mm,sss,sst = CallReductionInVoid
(ComparisonType,ll,ww,dd,eel,ee2,pp,vv,mm,sss,sst,PASS_FAIL,candidate,NONcandidate,counter)
            variables = ll,ww,dd,eel,ee2,pp,vv,mm,sss,sst

        if Model == 3:      #PERMEABILITY MODEL
            candidate,NONcandidate,PASS_FAIL,p_mdot,mm,pp,p_time,p_temp,p_pm = CallPermeability(Comp
arisonType,p_mdot,mm,pp,p_time,p_temp,p_pm,PASS_FAIL,candidate,NONcandidate,counter)
            variables = p_mdot,mm,pp,p_time,p_temp,p_pm

        if Model == 4:      #STRESS RELAXATION MODEL
            candidate,NONcandidate,PASS_FAIL,dd,sss,tt,ll,pp,sst,vv,ww = CallStressRelaxation(Compar
isonType,dd,sss,tt,ll,pp,sst,vv,ww,PASS_FAIL,candidate,NONcandidate,counter)
            variables = ll,ww,dd,pp,vv,sss,sst,tt

        if Model == 5:      #BURST MODEL
            candidate,NONcandidate,PASS_FAIL,ll,ww,dd,eel,ee2,pp,vv,sss,sst,t = CallBurst(Comparison
Type,ll,ww,dd,eel,ee2,pp,vv,sss,sst,t,PASS_FAIL,candidate,NONcandidate,counter)
            variables = ll,ww,dd,eel,ee2,pp,vv,sss,sst,t
```

```
        candidate_percentage = (float(candidate)/n)*100
        fail_percentage = (float(NONcandidate)/n)*100
        counter+=1

    plt.show()
    return candidate_percentage,fail_percentage,PASS_FAIL,variables
```

Graphs & Statistics:

In [ ]:
```
def CrossCorrelation(df1,df2,df3,A,B,A_pass,B_pass,A_fail,B_fail):
    sns.set(style="ticks")
    #All values
    sns.jointplot(x=A, y=B, kind="kde", color="#4CB391",data=df1)
    #Passed values
    sns.jointplot(x=A_pass, y=B_pass, kind="hex", color="#2CB391",data=df2)
    #Failed values
    sns.jointplot(x=A_fail, y=B_fail, kind="hex", color="#3CB391",data=df3)
    return
```

In [ ]:
```
def CrossCorrelation(df1,df2,df3,A,B,A_pass,B_pass,A_fail,B_fail):
    sns.set(style="ticks")
    #All values
    sns.jointplot(x=A, y=B, kind="kde", color="#4CB391",data=df1)
    #Passed values
    sns.jointplot(x=A_pass, y=B_pass, kind="hex", color="#4CB391",data=df2)
    #Failed values
    sns.jointplot(x=A_fail, y=B_fail, kind="hex", color="#4CB391",data=df3)
    return
```

In [ ]:
```
def Histogram(A,B,A_pass,B_pass,A_fail,B_fail,labelA,labelB):
    plt.hist(A_pass,50,edgecolor='k')
    plt.hist(B_pass,50,edgecolor='k')
    labels= [labelA,labelB]
    plt.legend(labels)
    plt.show()
    return
```

In [ ]:
```
def Plot3D(X,Y,Z,labelx,labely,labelz):
    fig=plt.figure()
    ax=fig.add_subplot(1,1,1,projection='3d')
    axis_font = {'size':'12'} #customize graph

    ax.scatter(X,Y,Z)
    ax.set_xlabel(labelx,**axis_font),ax.set_ylabel(labely,**axis_font),ax.set_zlabel(labelz,**axis_
font) #name axes

    #Convert the z-axis to pass/fail wording:
    ax.zaxis.set_major_locator(MaxNLocator(integer=True))
    ax.zaxis.set_major_formatter(plt.FuncFormatter(FormatFunc))

    plt.show()
    return
```

In [ ]:
```
def Statistics(A,B,A_pass,B_pass,A_fail,B_fail,labelA,labelB):
    # Generate summary statistics
    print(labelA,"candidates properties")
    print("Count:", len(A_pass))
    print("Mean: ", np.mean(A_pass))
    print("SD: ",np.std(A_pass))
    print("Max: ",np.max(A_pass))
    print("Min: ",np.min(A_pass))
```

```
    print("\n")

    print(labelB,"candidates properties")
    print("Count:", len(B_pass))
    print("Mean: ", np.mean(B_pass))
    print("SD: ",np.std(B_pass))
    print("Max: ",np.max(B_pass))
    print("Min: ",np.min(B_pass))
    print("\n")

    #Table of percentiles
    print("Percentiles for candidates properties:",labelA)
    p_tiles = np.percentile(A_pass,[5,10,15,25,75,85,90,95])
    for p in range(len(p_tiles)):
        l = [5,10,15,25,75,85,90,95]
        print("{}%-ile: ".format(l[p]).rjust(15),"{}".format(p_tiles[p]))
    print("\n")

    print("Percentiles for candidates properties:",labelB)
    p_tiles = np.percentile(B_pass,[5,10,15,25,75,85,90,95])
    for p in range(len(p_tiles)):
        l = [5,10,15,25,75,85,90,95]
        print("{}%-ile: ".format(l[p]).rjust(15),"{}".format(p_tiles[p]))
    return
```

In [ ]:

```
#Graphs calling function:
def AllGraphsFunc(df1,df2,df3,Prop1,Prop2,Prop1_pass,Prop2_pass,Prop1_fail,Prop2_fail,Prop1_label,Pr
op2_label,Prop1pass_label,Prop2pass_label,Prop1fail_label,Prop2fail_label):
    Histogram(Prop1,Prop2,Prop1_pass,Prop2_pass,Prop1_fail,Prop2_fail,Prop1_label,Prop2_label) #plot
s 1D histogram
    Statistics(Prop1,Prop2,Prop1_pass,Prop2_pass,Prop1_fail,Prop2_fail,Prop1_label,Prop2_label) #pri
nts the statistics
    CrossCorrelation(df1, df2, df3,Prop1_label,Prop2_label,Prop1pass_label,Prop2pass_label,Prop1fail
_label,Prop2fail_label) #plots 2D histogram
    #Plot3D(P_mass,P_pressure,PASS_FAIL,"Mass","Pressure","Pass or Fail")
    return
```

Main:

In [ ]:

```
1
#Main:
if ComparisonType == 1:
    fig, ((ax1,ax2),(ax3,ax4)) = plt.subplots(nrows=2,ncols=2, figsize=(14,12))
    plt.subplots_adjust(wspace = 0.6,hspace = 0.6)

if Model == 1:
    print("Inflation Model")
    candidate_percentage,fail_percentage,PASS_FAIL,(L_list,W_list,D_list,E1_list,E2_list,P_list,V_li
st,M_list,SS_list,ST_list) = MonteCarloSimulation(sim_it,1,ComparisonType)
    if ComparisonType == 2:
        E1_pass,E2_pass,L_pass,W_pass,D_pass,P_pass,V_pass,M_pass,SS_pass,ST_pass = zip(*[[E1_list[j
],E2_list[j],L_list[j],W_list[j],D_list[j],P_list[j],V_list[j],M_list[j],SS_list[j],ST_list[j]] for
j in range(len(PASS_FAIL)) if PASS_FAIL[j]==1])
        E1_fail,E2_fail,L_fail,W_fail,D_fail,P_fail,V_fail,M_fail,SS_fail,ST_fail= zip(*[[E1_list[j
],E2_list[j],L_list[j],W_list[j],D_list[j],P_list[j],V_list[j],M_list[j],SS_list[j],ST_list[j]] for
j in range(len(PASS_FAIL)) if PASS_FAIL[j]==0])
        df1 = pd.DataFrame({'All E1':E1_list,'All E2':E2_list})
        df2 = pd.DataFrame({'Passed E1':E1_pass,'Passed E2':E2_pass})
        df3 = pd.DataFrame({'Failed E1':E1_fail,'Failed E2':E2_fail})
```

```
        #Print Results
        print("Candidate material property pass rate = ", candidate_percentage, "%")
        print("Material property failure rate = ", fail_percentage, "%","\n")
        print("Number passed:", len(E1_pass))
        print("Number failed:", len(E1_fail))
        print("\n","Some of the candidate material properties:","\n",df2.head())
        AllGraphsFunc(df1,df2,df3,E1_list,E2_list,E1_pass,E2_pass,E1_fail,E2_fail,'All E1','All E2',
'Passed E1','Passed E2','Failed E1','Failed E2')


if Model == 2:
    print("Reduction In Void Model")
    candidate_percentage,fail_percentage,PASS_FAIL,(L_list,W_list,D_list,E1_list,E2_list,P_list,V_li
st,M_list,SS_list,ST_list) = MonteCarloSimulation(sim_it,2,ComparisonType)
    if ComparisonType == 2:
        E1_pass,E2_pass,L_pass,W_pass,D_pass,P_pass,V_pass,M_pass,SS_pass,ST_pass = zip(*[[E1_list[j
],E2_list[j],L_list[j],W_list[j],D_list[j],P_list[j],V_list[j],M_list[j],SS_list[j],ST_list[j]] for
j in range(len(PASS_FAIL)) if PASS_FAIL[j]==1])
        E1_fail,E2_fail,L_fail,W_fail,D_fail,P_fail,V_fail,M_fail,SS_fail,ST_fail= zip(*[[E1_list[j
],E2_list[j],L_list[j],W_list[j],D_list[j],P_list[j],V_list[j],M_list[j],SS_list[j],ST_list[j]] for
j in range(len(PASS_FAIL)) if PASS_FAIL[j]==0])
        df1 = pd.DataFrame({'All E1':E1_list,'All E2':E2_list})
        df2 = pd.DataFrame({'Passed E1':E1_pass,'Passed E2':E2_pass})
        df3 = pd.DataFrame({'Failed E1':E1_fail,'Failed E2':E2_fail})
        #Print Results
        print("Candidate material property pass rate = ", candidate_percentage, "%")
        print("Material property failure rate = ", fail_percentage, "%","\n")
        print("Number passed:", len(E1_pass))
        print("Number failed:", len(E1_fail))
        print("\n","Some of the candidate material properties:","\n",df2.head())
        AllGraphsFunc(df1,df2,df3,E1_list,E2_list,E1_pass,E2_pass,E1_fail,E2_fail,'All E1','All E2',
'Passed E1','Passed E2','Failed E1','Failed E2')

if Model == 3:
    print("Permeability Model")
    candidate_percentage,fail_percentage,PASS_FAIL,(P_mdot,P_mass,P_pressure,P_time,P_Temp,P_PM) = M
onteCarloSimulation(sim_it,3,ComparisonType)
    if ComparisonType == 2:
        mdot_pass,mass_pass,pressure_pass,time_pass,Temp_pass,PM_pass = zip(*[[P_mdot[j],P_mass[j],P
_pressure[j],P_time[j],P_Temp[j],P_PM[j]] for j in range(len(PASS_FAIL)) if PASS_FAIL[j]==1])
        mdot_fail,mass_fail,pressure_fail,time_fail,Temp_fail,PM_fail= zip(*[[P_mdot[j],P_mass[j],P_
pressure[j],P_time[j],P_Temp[j],P_PM[j]] for j in range(len(PASS_FAIL)) if PASS_FAIL[j]==0])
        df1 = pd.DataFrame({'All Permeability':P_PM,'All Temperature':P_Temp})
        df2 = pd.DataFrame({'Passed Permeability':PM_pass,'Passed Temperature':Temp_pass})
        df3 = pd.DataFrame({'Failed Permeability':PM_fail,'Failed Temperature':Temp_fail})
        #Print Results
        print("Candidate material property pass rate = ", candidate_percentage, "%")
        print("Material property failure rate = ", fail_percentage, "%","\n")
        print("Number passed:", len(PM_pass))
        print("Number failed:", len(PM_fail))
        print("\n","Some of the candidate material properties:","\n",df2.head())
        AllGraphsFunc(df1,df2,df3,P_PM,P_Temp,Temp_pass,PM_pass,Temp_fail,PM_fail,'All Permeability'
,'All Temperature','Passed Permeability','Passed Temperature','Failed Permeability','Failed Temperat
```

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